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METALS TECHNOLOGY LABORATORIES

Corrosion Protection of Underground Storage Tanks

Final Report by: G.I. Russell & Company Ltd.

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Final Report by:

G. I. RUSSELL & COMPANY LTD.,

Investigators: D. J. Carrigan, P. Eng.
J. P. Kosednar, P. Eng.
G. I. Russell, P.Eng.

Scientific
Advisor: W. W. Smeltzer, Ph.D., P. Eng.,

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FOREWORD

The Goals of this Applied Research Development Program

Since applying cathodic protection to electrically isolated buried pipelines, tanks and piping, the topside surfaces of many uncoated, or poorly coated tanks, the topside surfaces of only one or two tanks of a large group of tanks in tank farms, and the surfaces of risers of pipeline systems, and of piping connected to underground tanks; they have been at unacceptably low levels of cathodic polarization; however the bottom surfaces and all other surfaces of these tanks, pipelines, and pipe risers were all very highly polarized at potentials of up to -1200 mV, (to CSE).

It has also been found, that the entire buried surfaces of very well coated product lines connected, (but electrically isolated therefrom) to U.L.C. tanks installed since 1985 remained at a non-polarized potential; this condition could not be overcome by the driving potential of zinc, AZ63 alloy magnesium anodes, or of high potential magnesium alloy anodes. It was determined that impressed current applied to several of the galvanic anodes (now serving as a ground bed) increased their output of protective current to 2 mA to obtain the desired minimum polarized potential, of -850 mV (to CSE) indicating a high circuit resistance; however the rectifier driving potential was over 20 volts. Similar problems have been encountered with topsides of bare tanks with impressed current necessarily applied at up to 20 volts or more; even so, although their bottom surfaces were overprotected at polarized potentials exceeding -1200 mV to CSE, the topside surfaces remained unprotected.

(Foreword cont'd)

It has also been regularly found that portions of the upper surfaces of very well coated buried tanks installed since 1985 were not adequately protected, although their undersides were at very highly polarized potentials. These inconsistencies have been difficult to explain, or reconcile; this was disconcerting to those committed to uniformly prevent external corrosion of buried metallic tanks and piping structures.

Various reasons have been surmised for these non-uniform conditions, including the relatively poor conductivity of the sand or other granular backfills, and whether these were attributable to the presumed highly aerated, oily, or dry soil environment at these surface areas, or due to damaged or poor coating applications. It was only evident that the soil environment at these locations, must not be homogeneous, thus it was considered necessary to undertake this study in an attempt to find feasible ways to transform the solution chemistry of the backfills around the topside surfaces of underground tanks and around the risers of piping systems.

It is known that a uniformly conductive environment with a sufficiently alkaline interface between the soil and the exposed metal surface is required to obtain an optimum, uniform polarized potential at all points by cathodic protection. Thus it was decided that ways to uniformly increase the conductivity of the soil environment between the anodes and the entire surface area surrounding tanks and piping to minimize the current requirement by preventing oxygen diffusion to the soil/metal interface should be devised using environmentally acceptable chemical treatments. It was also determined that uniform polarization should be feasible without the need for impressed current - i.e., solely by the use of galvanic anodes.

1.0 EXECUTIVE SUMMARY

This applied research program was initiated after a very preliminary literature search to select a few candidate chemicals that should be considered; calcium hydroxide being thought to be a prime ingredient in any mixture; it was first decided to find out if additions of this one solution might have merit.

During late fall of 1988 (prior to contract award) very preliminary field applications of calcium hydroxide solutions to the uncoated topside surfaces of the two 15,000 gallon jet fuel storage tanks at Saint John, N.B. and of 8,000 gallon tanks of glycol and oil product storage tanks at Halifax.

The corroded topsides and ends of these tanks, uncovered to be closely examined for concentrated pitting, were only thinly covered over by the coarse backfill to provide furrows; a 10% solution of this electrolyte was poured in these furrows and soaked down over the sidewalls of these tanks. No marked improvement in cathodic protection however was measured within the short time available to remain on site.

Therefore having not so easily found a tangible solution, it was decided that a thorough literature search would first be required; then a comprehensive laboratory testing program would need to be conducted to select the appropriate mix of environmentally acceptable chemical ingredients; only then should the applied research program be conducive of successful results in future trial applications.

(1.0 cont'd)

During phase I of the laboratory research program, cathodic protection was applied to underground steel tanks utilizing uniformly corroded pipe to satisfy a modelling of 1:10. Three identical laboratory model "tanks" were assembled from a section of 10" diameter, uncoated, oxygen concentration cell corroded, steel pipe (APE 5L). The soil bed was chosen to simulate a typical well-aerated topside surface and a wetted bottom with drainage to occur through both the compacted sand on one-half the tank length, and granulated crushed stone screenings on the other half of its length. Appropriate reference carbon and zinc electrodes were positioned during backfilling and the potentials of these electrodes were monitored regularly by standard (CSE) surface electrodes.

Specimen #2 was used as the "Control", not being regularly subjected to any form of chemical treatment except for additions of water. Specimen #1 and #3 were periodically treated with various environmentally acceptable chemical solutions consisting of Ca(OH)2. The backfill for one specimen was altered by addition of Portland Cement. Potential measurements and electrochemical polarization affects were examined over a period extending from September/89 to March/90.

During Phase II of the laboratory research program, an investigation was carried out on the effect of stray a.c. current up to a very few volts at the soil/metal interface on a cathodically protected coated steel structure. The layout for the series of tests was arranged in a "soil-box" to simulate the environmental exposure conditions for a typical underground storage tank piping system.

(1.0 cont'd)

It was concluded from the investigations in Phase I of the laboratory research that:

.1 Chemical additions based on NaOH and $NaHCO_3$ only yielded rather temporary beneficial effects on cathodic protection electrochemical properties. This behaviour is attributed to the large solubilities inherent with these chemicals.

.2 Utilization of $Ca(OH)_2$ above had a nominally beneficial effect of more prolonged polarization but this polarization remained very non-uniform and inconsistent over a large range of polarization potentials.

.3 Utilization of a $Ca(OH)_2$ - $CaSiO_3$ slurry led to more beneficial cathodic protection but the protection was still inadequate in degree and uniformity of electrochemical polarization.

.4 The most effective chemical addition was obtained by a slurry of $Ca(OH)_2$ - $Ca(NO_2)$ -- $CaSiO_3$; this led to extremely effective cathodic protection involving stable polarization potentials on the entire tank surface at, for example, -840 mV vs. (CSE) or even at -740 mV vs. (CSE) and within a few millivolts. This beneficial effect is attributed to the increased ionic conductivity of the soil water, the depletion of oxygen at the soil/metal interface by the scavenging activity of $Ca(NO)_2$ during the initial stages of polarization, and the extreme stability of the $Ca(OH)_2$ - $Ca(SiO_3)$ film formed during polarization at the metallic surface.

(1.0 cont'd)

.5 Addition of Portland Cement to the backfill of either type (granulated stone or sand) also resulted in a beneficial effect on cathodic protection by reducing the current requirement to a density <60 mA/m2.

.6 It would appear from these above findings (1-5) that it would be wise to specify the addition of Portland Cement in the granular backfill of all new tank installations. Also top-side surfaces of poorly coated and bare tanks should be chemically treated with a Ca(OH)2 - Ca(NO2)2 - Ca(SiO3) slurry during the establishment of cathodic protection in order to obtain optimal prevention of corrosion. Those latter considerations apply to cathodic protection being applied by impressed current or sacrificial anodes.

It was concluded from the investigation in Phase II of the laboratory research that where stray a.c. current was superimposed on a structure under cathodic protection, the structure-to-soil potential became more positive; this indicated an adverse effect on cathodic polarization. This undesirable effect may be overcome by increasing the applied d.c. current.

The investigation performed under Phase II should be thought of as a macro look at the very low voltage effect of stray

a.c. on cathodically polarized structures. This work suggests that further study is needed to define the range of variables involved in order to optimize cathodic polarization.

1.0 RÉSUMÉ POUR LA DIRECTION

Ce programme de recherche appliquée a été lancé après un examen très préliminaire de la documentation dans le but de choisir quelques produits chimiques d'intérêt potentiel pour l'utilisation recherchée; l'hydroxyde de calcium étant réputé être un constituant fondamental de tout mélange, il a d'abord été décidé d'examiner si des additions de cette solution peuvent présenter des avantages.

A la fin de l'automne 1988 (avant l'adjudication des contrats), on a procédé à des applications très préliminaires de solutions d'hydroxyde de calcium sur les surfaces du dessus non revêtues des deux réservoirs de carburéacteur de 15 000 gallons à Saint-Jean (N.-B.) et de réservoirs de glycol de 8000 gallons et de réservoirs de produits pétroliers à Halifax.

Les dessus et les extrémités corrodées de ces réservoirs, mis au jour pour examiner de près les concentrations de piqûres, ont été à peine recouverts du remblai grossier pour former des sillons; une solution contenant 10 % de cet électrolyte a été versée dans les sillons et s'est infiltrée sur les parois latérales de ces réservoirs. Aucune amélioration de la protection cathodique n'a toutefois été observée pendant la courte période réservée à cet essai sur le terrain.

Par conséquent, n'ayant pas réussi à trouver facilement une solution concrète, il a été décidé qu'il fallait procéder à une étude poussée de la documentation; puis, il faudrait mener un programme détaillé d'essais en laboratoire pour choisir le mélange approprié de constituants chimiques acceptables pour l'environnement; ce n'est qu'ensuite que le programme de recherche appliquée pourra porter fruit dans des applications expérimentales futures.

Pendant la phase I du programme de recherche en laboratoire, la protection cathodique des réservoirs en acier enfouis a été étudiée à l'aide d'un tuyau uniformément corrodé se prêtant à une modélisation au 1/10. Trois modèles réduits de "réservoirs" identiques ont été montés à partir d'une longueur de tuyau en acier (APE 5L) de 10 po de diamètre, sans revêtement, corrodé en cellule de concentration d'oxygène. Le lit de sol a été choisi de façon à simuler une couverture bien aérée type et un fond mouillé avec drainage à travers le sable tassé sur une moitié de la longueur du réservoir et du concassé tamisé sur l'autre moitié de la longueur. Des électrodes de référence appropriées en carbone et en zinc ont été mises en place pendant le remblayage, et les potentiels de ces électrodes ont été contrôlés régulièrement par des électrodes de surface étalons en calomel (ÉSC).

L'échantillon no 2, utilisé comme "témoin", n'a pas été soumis régulièrement à aucune forme de traitement chimique à l'exception d'addition d'eau. Les échantillons no 1 et no 3 ont été périodiquement exposés à diverses solutions de $Ca(OH)_2$ acceptables pour l'environnement. Le remblai pour un échantillon a été modifié

par l'addition de ciment portland. Les mesures de potentiel et les effets de polarisation électrochimique ont été examinés pendant une période allant de septembre 1989 à mars 1990.

Pendant la phase II du programme de recherche en laboratoire, une étude a été menée sur l'effet des courants parasites c.a. allant jusqu'à quelques volts à l'interface sol/métal dans un élément en acier avec revêtement et protection cathodique. Le montage pour la série d'essais a été placé dans une "plate-bande" pour simuler les conditions ambiantes d'exposition d'une tuyauterie de réservoir souterrain type.

La phase I du programme de recherche en laboratoire a permis de conclure que:

1 L'addition de solutions de NaOH et de $NaHCO_3$ n'améliore que temporairement les propriétés électrochimiques de protection cathodique. Ce résultat tient à la grande solubilité de ces substances.

2 L'utilisation de $Ca(OH)_2$ sur le dessus prolonge théoriquement la polarisation, mais cette polarisation est très irrégulière et très erratique dans une grande gamme de potentiels de polarisation.

3 L'utilisation d'une suspension de $Ca(OH)_2$ - $CaSiO_3$ améliore la protection cathodique, mais cette dernière reste insuffisante en termes de degré et d'uniformité de la polarisation électrochimique.

4 La solution la plus efficace est une suspension de $Ca(OH)_2$ - $Ca(NO_2)$ - $CaSiO_3$ qui se traduit par une protection cathodique très efficace attribuable à des potentiels de polarisation stables sur toute la surface des réservoirs, par exemple à -840 mV par rapport à l'ÉSC ou même à -740 mV par rapport à l'ÉSC et à quelques millivolts près. Cet avantage tient à la conductivité ionique accrue de l'eau du sol, à l'épuisement de l'oxygène à l'interface sol-métal dû à l'effet d'entraînement du $Ca(NO)_2$ au début de la polarisation, et à l'extrême stabilité de la pellicule de $Ca(OH)_2$ - $Ca(SiO_3)$ qui se forme pendant la polarisation à la surface métallique.

5 L'addition de ciment portland dans l'un ou l'autre des remblais (concassé ou sable) améliore la protection cathodique en réduisant l'appel de courant à une densité de moins de 60 mA/m^2.

6 Les résultats susmentionnés (1-5) semblent indiquer qu'il serait prudent de recommander l'addition de ciment portland dans le remblai de granulat de toute nouvelle installation de stockage. En outre, les surfaces de dessus des réservoirs mal ou non revêtus devraient être traitées chimiquement au moyen d'une suspension de $Ca(OH)_2$ - $Ca(NO_2)_2$ - $Ca(SiO_3)$ pendant l'établissement de la

protection cathodique pour offrir une protection optimale contre la corrosion. Ces dernières remarques valent pour une protection cathodique assurée par un courant appliquée ou par des anodes sacrificielles.

La phase II du programme de recherche en laboratoire permet de conclure que, lorsqu'un courant alternatif parasite traverse un élément avec protection cathodique, le potentiel élément-sol devient plus positif,ce qui réduit la polarisation cathodique. Cet effet indésirable peut être compensé par l'application d'un courant continu plus élevé.

L'étude de la phase II doit être considérée comme une vue d'ensemble des effets de très faible tension des courants alternatifs parasites sur les éléments présentant une polarisation cathodique. Elle révèle qu'il faudrait approfondir le sujet pour définir la gamme des variables en jeu de manière à optimiser la polarisation cathodique.

2.0 BACKGROUND

2.1 Basic Factors Involved in Uniformly Preventing Corrosion of Underground Steel Storage Tanks

2.1.1 pH and Aeration Control

Until about 1975 most underground steel storage tanks were usually only painted or coated black with a bituminous cold applied mastic, and backfilled with sand. Tank holddown straps were not usually isolated until ULC specifications were adopted (where applicable) and this manufacturer's standard required either coal tar epoxy or plastic tape wrapping to be applied. However, due to the lack of coating application facilities and/or coating inspection, and widespread use of the option to apply relatively inexpensive, but ineffective green plastic tape wrappings, a large proportion of the ULC tanks were very poorly separated from their environment until about 1980, when most tank manufacturer's were applying coal tar epoxy coatings. The initial benefit of the ULC standards was that most tanks installed from 1975, to 1980 for storage of combustible or flammable products, were electrically isolated from contact to their holddown straps and connected piping; however the great majority of tanks installed prior to about 1980 were in effect, poorly coated.

2.1.2 ULC standards published in 1973 also specified an A.S.T.M. structural alloy to be used as a high potential magnesium anode until permission was finally granted to use the higher potential anode alloy; during recent years the lower potential zinc plate anodes, were mounted at tank ends by the manufacturer (instead of magnesium anodes mounted to be clear of the surface of the tank in the otherwise similar STI standard widely used throughout U.S.A.). Therefore, galvanic current outputs were proportional to the .9, .7 and .25 net driving voltages between galvomag or equal high anode alloy potential AZ63 magnesium alloys, or A.S.T.M. magnesium alloy, or zinc anodes, - and the protected tank, respectively. The much lower driving voltage of zinc greatly reduced the change of a uniform polarized potential, at the topside surfaces in particular, but it was also found that due to the lack of the normal tack-welded contact to cast-in electrogalvanized steel core, and/or the use only of gypsum board as the selected backfill, many zinc plate anodes became inactive.

2.1.3 In addition, it is suspected that spillage of gasoline around the fill pipes (at the low ends of tanks) has resulted in deterioration of even the more effective coal tar epoxy coating, and that the greatest coating damage occurred on the topsides. This may partially account for the often inadequate current density measured at the topside surfaces of coated tanks. In any case the upper surfaces of most protected tanks

(2.1.3 cont'd)

surveyed are at a non-uniform polarized potential, or at an applied potential that is less negative than -850mV to the CSE reference electrode, ie., CSE.

2.1.4 It has been concluded therefore after having annually surveyed thousands of buried tanks installed throughout the country, most of which are poorly coated or uncoated, that the exposure of bare steel is much greater at their highly aerated topsides where the protective coating is needed most. Therefore placement of all anodes of whatever type specified should not always be close to or adjacent to the bottom of the tanks.

2.2 <u>The Technological Problem</u>

2.2.1 The high demand for protective current density at the topside surfaces may be attributed to the use of granular backfill. Sand backfill has most often been specified for underground steel storage tanks, in order to distribute the soil pressure and and to provide a clean soil/metal interface by excluding the use of contaminated excavated materials. However, the sand must be watered down and compacted in place; also, during the course of backfilling, workmen walk over and handle materials to damage and often scrape the topside coating application. Where sand backfill is not available, granular and stone dust or even crushed

(2.2.1 cont'd)

slag, shale, or stone have been used. Also, due to lack of care or where no specifications were provided, the spoil was backfilled directly upon the tank surface. Thus a large proportion of buried tanks are found to be backfilled in stone although pea gravel has recently been widely specified to meet te requirements of the environment projection acts.

Specifications ordinarily required at least 2 ft. of ground cover, except where subjected to vehicular traffic, where 3 ft. of cover is required. However, the water table is usually 5 to 20 ft. below grade level; and tanks are often under pavement most often, therefore, the sand or other granular backfill dries out to provide a highly aerated exposure over most of the tank surface, except for the more wetted bottom.

2.2.2 Salts and soil chemicals wash down percolating through more voids and the porous backfill to the topsides, to collect at depth and fill the bottom of the sand backfilled tank excavation, where sediments are trapped; therefore, the soil/water solution at the bottom usually becomes stagnant, deaerated, and its solution more concentrated, than the surrounding soil solution chemistry. As a result, penetrations causing leaks due to corrosion predominately occur in the bottom quadrant at holidays or scraped and damaged

(2.2.3 cont'd)

areas exposed to this more highly conductive, anaerobic environment. Due to this close coupling of a small anodic area at the bottom, to a very large cathodic area of metal exposed to highly aerated, well drained sand backfill over the topsides, the rate of pitting corrosion is most severe on the bottom.

Small diameter tanks and those of thin about 1/8" outer wall metal are much more quickly penetrated, therefore, than are 3/8" wall, larger diameter tanks. In addition because corrosion concentrates at holidays, very well coated and thin-walled tanks are perforated at the bottom extremely quickly compared to poorly coated or bare heavy wall large diameter tanks.

2.2.3 An even more severe loss of metal due to this exposure condition occurs with storage tanks that are installed so that only 50% to 75% of the tank is belowgrade, these tanks having been backfilled over to provide 3 ft. of cover abovegrade. These tanks are often installed with their bottoms in shale or soft rock, above hard underlying strata which are usually less permeable. Again, pitting type corrosion is concentrated, therefore, to the bottom surface area. But the prime cause of this pitting is the strong chemical battery generated by this bottom area being

(2.3.1. cont'd)

coupled to the very highly cathodic and much larger surface area exposed to well aerated soil over the shale or rock.

2.3 Anode Placement for Galvanic and Impressed Current Systems for Cathodic Protection

2.3.1 Magnesium and impressed current anodes are usually specified to be distributed in the bottom of the excavation for the tanks, or are to be drilled in within about 2 ft. of the sides and ends of the tanks, to about the depth of the tanks. Anodes laid horizontally are usually entirely within wetted or very moist ground, whereas the upper portions of vertical anodes are often in dryer soils of higher resistivity; thus, as to be expected, these anodes fail preferentially. Also, the cathodic protection "window" of 300 to 350 mV is narrow for this application re: the a maximum polarized potential is about -1200 mV (to CSE) to avoid the damaging effects of hydrogen evolution at the bottom tank surface, whereas the minimum polarized potential is about -850 mV (to CSE) at the topsides. An attempt to uniformly prevent corrosion, is often not feasible because the maximum useful (to avoid hydrogen evolution) applied potential may not exceed about 2 volts for most of these

(2.3.1. cont'd)

applications: it is noted that the 'IR' drop error included within the applied potential may then be about 200 to 300 mV greater than its correct polarized potential. Accordingly, impressed current anodes should either be remote, or if placed close to the tanks, their driving potential should be limited to a very few volts.

2.3.2 Placement of anodes close to the bottom sides of the tanks, or vertically alongside the tanks and within about 1 ft. in multiple tank installations, usually results in a very wasteful evolution of hydrogen, especially where protective current is impressed.

Thus, the specified utilization of impressed current to be applied at voltages far in excess of 6 volts - commonly specified to operate up to 12 and even 48 volts d.c. - has been considered extremely impractical. Instead for most applications, where impressed current is to be driven at high voltages, the anodes should be located as remotely as feasible from the buried tank/piping structure or system. The importance of remote anode placement is also greater for impressed current systems, due to the need to mitigate d.c. stray current where potential differences are significant across the remotely bonded electrical

(2.3.2. cont'd)

isolations at connections to the tank; the IR drops should be well within about 10% maximum of the 300 to 350 mV negative shift measured while cathodic protection is applied. This is why the potential difference between tanks and piping at these isolations should not exceed about 10 to 20 mV, in order to avoid prejudicing the required uniform polarization shift, and significant stray current interference. Furthermore, many tank connections involve the use of flexible expansion joints: these cause circuit resistances which may greatly increase the 'IR' drops between bonds and current carrying lead connections to the negative output of the rectifier.

2.3.3 By design therefore, it is always most important to apply cathodic protection at a minimum applied voltage, and to minimize the applied current to secure a uniform polarized potential of -850 to -1150 mV (to CSE). Excessive current density at any point results in a highly caustic exposure at the soil/metal interface; high alkalinity destroys the protective coating and/or its bond to the metal substrate due hydrogen evolution, and/or significant stray current interference. Designing for a uniformity of cathodic protection has always proven therefore to be the key to cost-effective results.

2.4 Compatibility of Tank Installation Specifications with Cathodic Protection.

2.4.1 The problem is that the current density requirement for cathodic protection is usually about 25 times or more greater at aerated surfaces, than it is at anaerobic exposures. This is why 90 to 95 percent of the demand for protective current density at both the coated and bared steel surfaces of tanks in aerated soils is usually at the topside aerated surfaces.

2.4.2 Oxygen concentration cell corrosion of the surfaces of underground storage tanks occurs similarly on unprotected pipelines. Although most pipelines are usually of smaller diameter, leaks first usually occur at the underside of the pipe in flat uniform soils, and their occurence is concentrated in swales and swamps when crossing rolling land. By design, per NACE recommended practises, for example, the coating on the cathodic surface should be comparatively superior to mitigate this strong chemical battery between top and bottom surfaces. For example, it is most important to doubly well coat pipe risers because these are to be exposed to more highly aerated soils. Also clean native soil has proven to be the preferred backfill for pipelines, as compared to the coarse sand, and crushed stone gravel or shale commonly specified to be backfilled around tanks and piping installations. These coarse backfills are therefore considered to be a

(2.4.2 cont')

prime cause of the severity of the corrosion problem, the relatively shorter average life expectancy without cathodic protection of about 8 to 12 years, for tanks as compared to 15 to 20 years for pipelines.

2.4.3 Many buried storage tanks are up to 10 to 12 ft. in diameter, as compared to up to a third of those larger diameters for the largest gas pipelines: tanks are usually buried much deeper and in porous sand and stone, and until recently have not been specified to be nearly so well coated as for pipelines. Where excavation is difficult and the tanks are covered over abovegrade, loss of metal due to corrosion attack in general, is therefore much more severe than for pipelines. The cathode/anode surface ratio, due to the difference in electrochemistry between topsides and bottomsides of tanks, most often is very much greater than for pipelines.

2.4.4 It is standard good practice to measure the tank to soil potentials over the top surface where cathodic protection is found to be usually minimal; however if tank to soil potential readings were also regularly taken between and to either side of the tanks it would be also known that adequate protective current is available; most often current is being applied at an adequate driving potential - except perhaps in the case

(2.5.2 cont'd)

of zinc anodes. Thus the current density requirement should be were should be uniform: however, most of the protective current is at the topside surfaces. Therefore anodes should be both remotely placed and in proximity near the top sides of tanks, or a superior protective coating application should be applied to the topside surfaces in particular - or the soil chemistry should be altered to result in this desired uniform surface condition.

2.5 Compatibility of Standards for Cathodic Protection of Underground Tanks

2.5.1 Various for-profit trade associations, whether this may be by lack of knowledge or concern, have addressed the corrosion problem by utilizing this technological solution to the limits of their vested interests.

2.5.2 ULC, initially concerned solely with the continued integrity of the tanks which carry their label, (as was the Steel Tank Institute in the U.S.A. or S.T.I.) isolated the tanks; this organization necessarily extended their interests only when the insurers, government bodies, or whomsoever requested this standard to include the pressure piping, and then, finally the suction piping. It is presumed to be for this reason that the U.L.C. standards restricted the

(2.5.3 cont'd)

end-user to produce all protective current from galvanic anodes only (and initially to the use of only specified galvanic metals which were of a composition not metallurgically designed to provide efficient performance as sacrificial anodes).

2.5.3 PACE on the other hand attempted by their standard to protect all metallically interconnected structures in common, by applying impressed current only. Usually it is not feasible however, to obtain the required polarized potential on a steel surface, which is closely coupled to the electrical grounding network - a massive surface area primarily of reinforcing steel in concrete, or of bare copper grounding cable (it is neither technically feasible nor even possible, to uniformly prevent corrosion while the primary structure is not electrically isolated). It is noted that the initial standard required the negative pole of the rectifier to be bonded directly to the electrical grounding network; this stipulation has not yet been deleted in this standard, although most installers have learned to ignore this requirement, in their attempt to obtain favourable structure-to-soil potential data. However the primary problem with PACE systems is the need to maintain electrical continuity bonds to piping, using clamps which are specified to be installed

(2.5.3 cont'd)

belowgrade, these connections may be bolted or copper-to-steel clamps, which often soon develop contact resistance. This need to compromise on the need for effective electrical isolations as for example at dispensers, (often these are mounted on steel reinforced pads mechanically connected to copper grounding) is contrary to long established recommended practises for corrosion prevention.

Unfortunately both of these and similar standards may also be adopted into for example, the Gasoline Handling Act.

2.5.4 Therefore, whereas such requirements in these standards, compromise the performance of cathodic protection, those standards are referred to for example in the National Fire Code of Canada, and those published by the Canadian Standards Association, et al; most of these standards also require or recognize the need to meet the requirements in NACE Standard Recommended Practices, although they may require an accredited NACE Corrosion Specialist to design, commission or survey the system; however it is not feasible for qualified professional corrosion engineers to compromise and remain excluded from this scope of work. It is unfortunate therefore that accredited NACE Corrosion Specialists did not constitute a concensus during the preparation of these governmentally accepted standards or that the NACE standards are not given precedence.

2.6 State of the Art Criteria for Uniform Corrosion Prevention by Cathodic Protection

2.6.1 NACE, the National Association of Corrosion Engineers, is a non-profit organization specializing in corrosion science and engineering, and publishes Recommended Practice Standards; which are regularly revised by the consensus process. Standards are published applying cathodic protection to buried metallic structures. Separate standards are published for buried and ongrade tanks and piping, and for pipelines. Each of these primary structures is required to be permanently electrically isolated, not only to minimize the current requirement, but to avoid stray current interference to foreign structures and to obtain a truly cathodically polarized surface. Therein, electrical continuity by welding, or equal, is considered to be a prerequisite; whether the structure should be designed to be galvanically protected, or protected by impressed current, or by both; these needs are normally determined by the NACE specialist, using the applicable API, NFPA, IP and other applicable standards, regulations, and safety codes, including the the Canadian or other National Electrical Code, (in order to protect the safety of personnel and of operations). Also, inaccessibly buried electrical isolations are not recommended in the NACE Recommended Practise Standards. It is just not feasible therefore for an experienced and accredited NACE Corrosion Engineer to design "by numbers" to any of these other standards and comply to the intent in "Performance Standards" provided by NACE.

2.6.2 The need for the surface of a buried steel structure to be at a minimum current-interrupted or polarized potential of -850 mV (to CSE) to know cathodic protection is uniformly applied, has always been the most generally recognized criterion. It has also been recognized, however, that unprotected buried steel may be at a "native" potential as anodic as -890 mV (to CSE), and as positive as about -400 mV in natural soils, even as positive as -200 mV (to CSE) in, for example, in highly oxygenated porous soils, mica, sand or shale. Thus, the average potential given for a steel surface in soil of -550 mV (to CSE) is highly variable, within a range of about $\pm$350 mV (to CSE).

The the seldom used optional criterion given in NACE standards to shift the native potential to a polarized potential of 100 mV in the negative direction may bein correctly utilized. However, in order to be certain corrosion remains uniformly prevented, corrosion engineering specialists should also observe that the polarized potential remains constant, the permissible rate of depolarization should only be up to a few millivolts within a few seconds after a current interruption. This is considered to be the quality criterion, one that has been required to be obtained in order to provide professional certifications that corrosion is permanently prevented at all surfaces of buried metallic structures by cathodic protection. This is why it is believed all standards for this

(2.6.2 cont'd)

application should be "performance standards" by design and application; qualified NACE accredited corrosion engineering specialists should be free to use their best judgement.

2.6.3 Based on unrecognized NACE or equal performance standards being applicable (other than those requirements anomalous to for example ULC and PACE), one goal of this research and development program is to devise the means to obtain and to permanently establish and define this uniform minimal rate of depolarization criterion for cathodic protection - with particular emphasis to the aerated surfaces at topside surfaces of underground tanks.

2.7 Comparison of the Feasibility of Uniformly Preventing Corrosion of Uncoated Pipelines and Tanks

2.7.1 Those concerned with old underground tanks should be aware of the completely suocessful results in permanently protecting uncoated steel pipelines built prior to 1940; no corrosion leaks have since been reported for over 50 years, as compared to the great many leaks having previously occurred annually thereto during the initial 10 to 15 years of service. Thus, it is assumed that uncoated steel tanks may be similarly preserved by cathodic protection, and whether the

(2.7.1 cont'd)

protective current is applied either through the use of galvanic and/or impressed current anodes.

2.7.2 The similarity between buried pipelines and tanks differs in only two major respects; most pipelines are longer and of smaller diameter than most tanks. Therefore, only the long line currents generated on pipelines by differential aeration enroute, can be matched by the large vertical exchange of current between the bottom of the tank in a relatively anaerobic environment, and the topside surface within a relatively aerated exposure. It has become supremely evident that this elected-chemical battery is compounded for tanks, and is the prime concern to be addressed, particularly for tanks which are partially buried and covered-over abovegrade.

2.7.3 Successful cathodic protection of old uncoated pipelines was based on the recognized prerequisite to electrically isolate the primary structure and to minimize the current density by uniformly distributing the protective current by remote placement of anodes; the goal was to cathodically protect well within the applied pipe-to-soil potential range of about -1000 to -1300 mV (to CSE) to obtain a polarized potential within the min/max range of about -800 mV to -1150 mV (to CSE). It was also often determined that a

(2.7.3 cont'd)

uniformly polarized pipe-to-soil potential of about -800 mV may be quite adequate to uniformly prevent corrosion in uniformly alkaline soils, where polarized potential values more negative than -1000 mV caused rapid deterioration of poor coating applications; subsequently higher current densities were thereby avoided. Therefore the need to minimize the current requirement was heretofore emphasized, by designing to provide a current density that was as uniform as feasible.

2.7.4 The standard over-the-line current interrupted pipe-to-soil measurement technique used to survey large diameter pipeline systems, in particular, has been to regularly measure directly over and to either side of the line to ensure protective current is being provided at a polarized potential more negative than -850 mV (to CSE) to the upper surfaces. It is obvious that this survey technique should be an even more important criterion to use to determine the effectiveness of cathodic protection provided for underground tank applications. In addition, to know corrosion is prevented, the negative potential shift of the surface (the structure-to-soil polarized potential, as compared to its original or natural structure-to-soil potential before cathodic protection) should usually exceed 300 mV (i.e., seldomas little as -100 mV.) Also, while

(2.7.4 cont'd)

current is interrupted, it was found that the rate of cathodic depolarization of the protective film should be very slow. All of these criteria and other techniques to know corrosion is prevented are considered in this research and development program.

2.7.5 It is noted that the sometimes mandatory requirement of -950 mV (to CSE) to be the minimum structure-to-soil polarized potential that can be accepted, or even the less stringent minimum polarized potential of -850 mV (to CSE) has often proven to be neither cost-effective nor always necessary to prevent corrosion. In fact, when this criterion of protection has been enforced or otherwise improperly applied to cold expanded gas transmission line pipe and offshore structures of high strength steel, for example, hydrogen embrittlement or HSC has become the major technological problem, one that may not be readily resolved. This criterion may not need to be applied to painted or poorly coated pipe: this mandatory high level of protection resulting in overprotection produces a more highly caustic environment at the soil/metal interface, which quickly disbonded or deteriorated poorly applied or poorly selected coatings. In addition, the calcareous deposition at the highly protected cathodic surface proved to be significantly more porous, and therefore

(2.7.5 cont'd)

inferior, to the homogeneous tight scale formation where the optimum polarized potential to uniformly prevent corrosion was applied at a much lower current density. Therefore, the need to not unnecessarily exceed the minimum polarized potential, or current interrupted structure-to-soil potential of -800 mV (to CSE), and the need to avoid approaching the hydrogen evolution potential of -1200 mV (to CSE) is also duly emphasized, and evaluated, throughout this research and development program; "gently applied cathodic protection which obtains a minimum uniform polarized potential, with minimal "IR" drop within the structure or in the soil, can only be achieved it is believed, i.e., where the soil chemistry has been uniformly transformed to be anaerobic at all soil/metal interfaces of the underground tank system."

2.8 The Feasibility of Applying a Uniform Polarized Potential to State-of-the-Art Criteria at the Corroded Surface of Existing Underground Bare Steel Tanks

2.8.1 An investment in cathodic protection is only guaranteed after the underground tank system has passed a tightness test and internal corrosion pitting is known to be minimal. Whereas external loss of metal can be expected to be concentrated at a few large pits on the bottom of bare tanks, the upper sides and ends are usually highly pitted in general but with a comparatively great loss of metal of the general wastage type as a result of oxygen concentration cell attack.

2.8.2 At well aerated exposures, native or natural top surface steel-to-soil potentials should be at about -400 mV (to CSE), or even more positive as a result of oxygen concentration cell activity. However, anaerobic bacterial type corrosion may have induced anodic potentials as negative as -890 mV (to CSE) within the corroded crevices of pits. Thus, the short lengths of pipes used to simulate corroded tanks were selected to have been severely and uniformly corroded by long exposure to this oxygen concentration cell type pitting.

2.8.3 Sections of pipe from corroded riser piping were accordingly obtained to approximate the worst conditions to be expected in-situ on the topsides of

(2.8.3 cont'd)

buried tanks, to simulate the required protective current density found to be in the order of 25 times greater on the topsides than on the bottom surface of the buried tanks. A scale of about 100 to 1 was selected in preparing each of the three tank specimens studied in this research program.

3.0 LABORATORY APPARATUS - pH and Aeration Control

.1 Laboratory Model

Three identical laboratory model "tanks" were assembled from a section of (254 mm) (10") dia. 273 mm (10.75" O.D.) uncoated, oxygen concentration cell corroded steel pipe. Each model was 356 mm (14") long; 305 mm (12") of its length was exposed, plastic pipe caps being used to seal each pipe end. Therefore, the exposed surface area of each of the specimens was 0.262 sq. m. (2.814 sq. ft.)

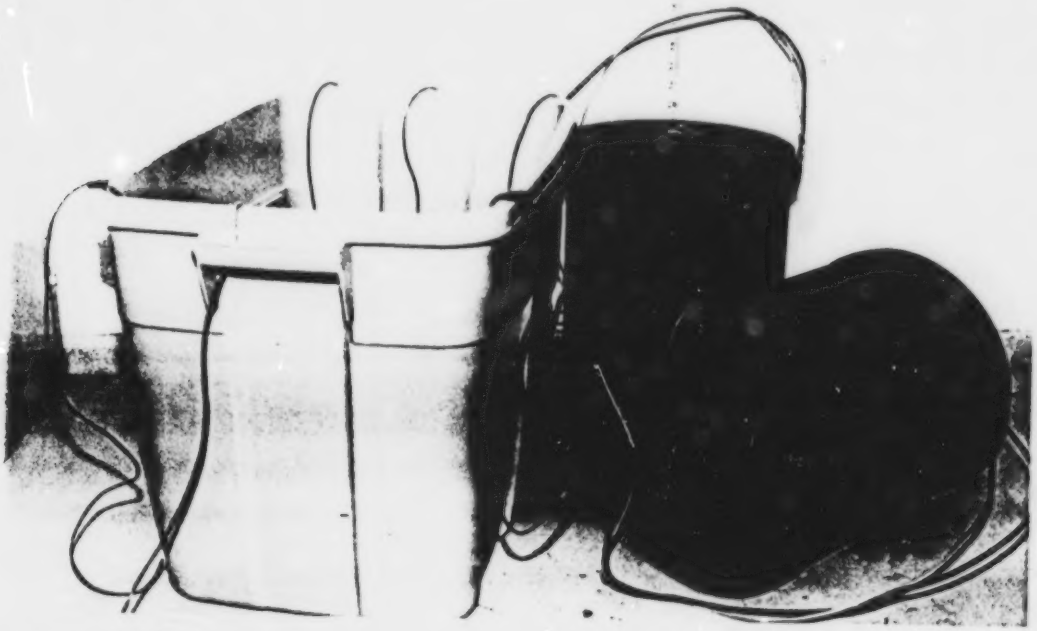
Each "tank" specimen was provided with two insulated No. 10 lead wires; one lead was used as the current-carrying conductor, the other as the potential sensing lead wire. (Photograph #1)

.2 References/Anodes

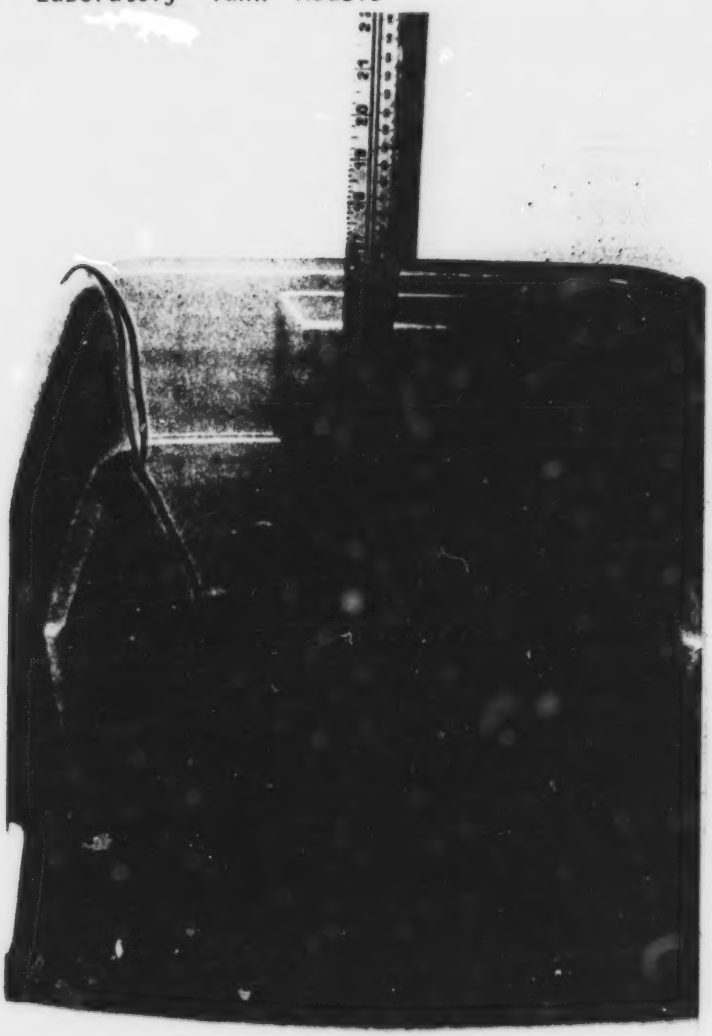
Ten graphite electrodes were provided for each model. Each electrode measuring 12 x 12 x 76 mm (1/2" x 1/2" x 3"), was provided with a #12 AWG TWU insulated copper wire.

Four graphite electrodes buried in saturated sand were used as impressed current anodes; six graphite electrodes were used as references to measure pipe-to-soil potentials, two directly below, and four directly above each "tank."

In addition to the six graphite reference electrodes, two zinc reference electrodes were provided for each specimen.



Photograph #1,
Laboratory "Tank" Models



Photograph #2,
Graphite Anode Positioning

(3.3 cont'd)

.3 Experimental Setup

Each of the specimens was buried in identical plastic basins (Figure 1) with a base dimension of 305 mm w x 457 mm l., (12" w x 18" l), and a depth of 406 mm (16"). Two drains were provided approximately 76 mm (3") above the bottom of each basin, to facilitate a constant water table being maintained at this level.

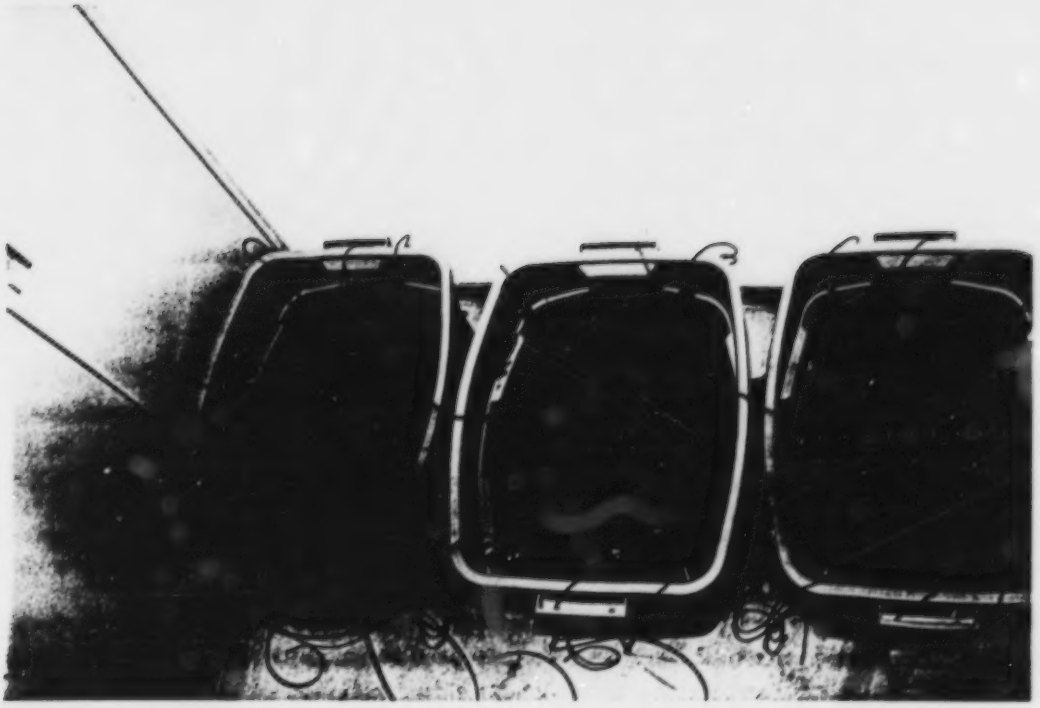
.4 Specimen Assembly

A 76 mm (3") layer of clean sand was placed and compacted in the bottom of each basin; this layer corresponded to the 100% saturation zone (below the water table).

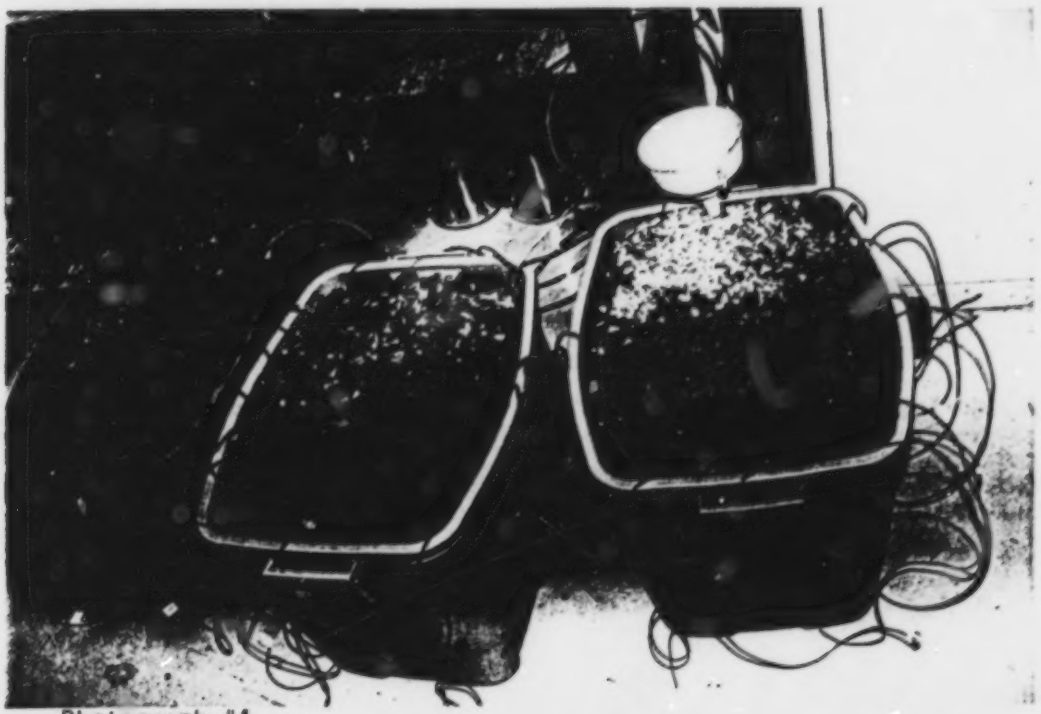
Four graphite electrodes placed in this layer of soil (one in each corner) were used as impressed current anodes. (Photograph #2)

The "tanks" were positioned to contact their bottom surfaces with the level of the water table. Two graphite electrodes placed directly beneath the center of each tank were used as reference electrodes, to measure pipe-to-soil potentials.

The tanks were backfilled using clean sand over one half, and stone screenings over the other half of their length, to simulate field conditions and the exposure characteristics to be studied with these commonly used backfill environments. (Photographs #3, and 4)



Photograph #3,
Partially Backfilled "Tanks"



Photograph #4,
Complete Specimen Assembly

(3.4 cont'd)

Two zinc references were positioned at the sand/gravel interface on either side of each "tank". Four graphite references were distributed and centered at the top of each "tank" to measure tank to soil potential and polarization effects in these highly aerated sand/gravel backfills, (Figure 1).

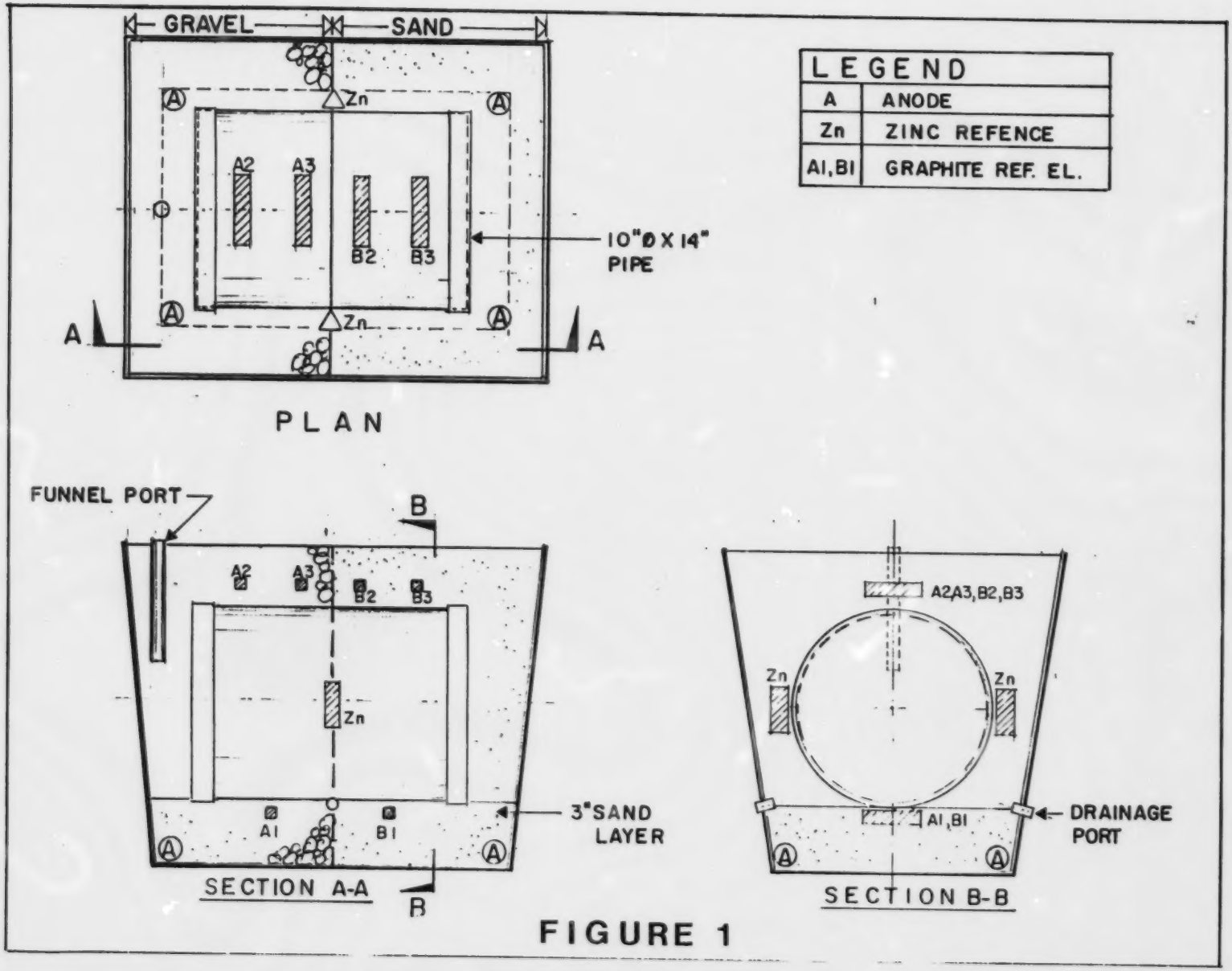

GRAVEL
SAND
Zn
A2
A3
B2
B3
10"Ø X 14" PIPE
A
A
PLAN
LEGEND
A ANODE
Zn ZINC REFENCE
A1,B1 GRAPHITE REF. EL.
FUNNEL PORT
B
A2
A3
B2
B3
Zn
A1
B1
3"SAND LAYER
SECTION A-A
B
A2A3,B2,B3
Zn
Zn
A1,B1
DRAINAGE PORT
SECTION B-B

FIGURE 1

4.0 LABORATORY PROCEDURE -pH AND AERATION CONTROL

.1 Three separate "tank" specimens were prepared on September 15, 1989 (in accordance with Section 3.0) and were connected in parallel to a common d.c. power source on September 18, 1989 (Figure 2). The applied or anode to cathode driving voltage remained equal for each of three models, but the current output varied depending on the resistance of each circuit.

.2 The d.c. output of the rectifier was adjusted, as required, while attempting to apply a "tank to soil" optimum polarized potential of cathodic protection. (Refer to Appendices A through F for a chronological record of output adjustments).

.3 Specimen #2 was used as the "Control", not being subjected to any form of chemical treatment. Whenever the backfill in either of the other two specimens was treated with a chemical solution, an equivalent volume of distilled water was added to Specimen #2, to maintain reasonably similar moisture content in the environment for each specimen.

.4 Specimens #1 and #3 were periodically treated with various environmentally acceptable chemical solutions.

Specimen #1 was initially treated with nitrogen gas and a $Ca(OH)_2$ solution on October 23rd, 1989. Subsequent additions involved the application of a $NaHCO_3$ solution used

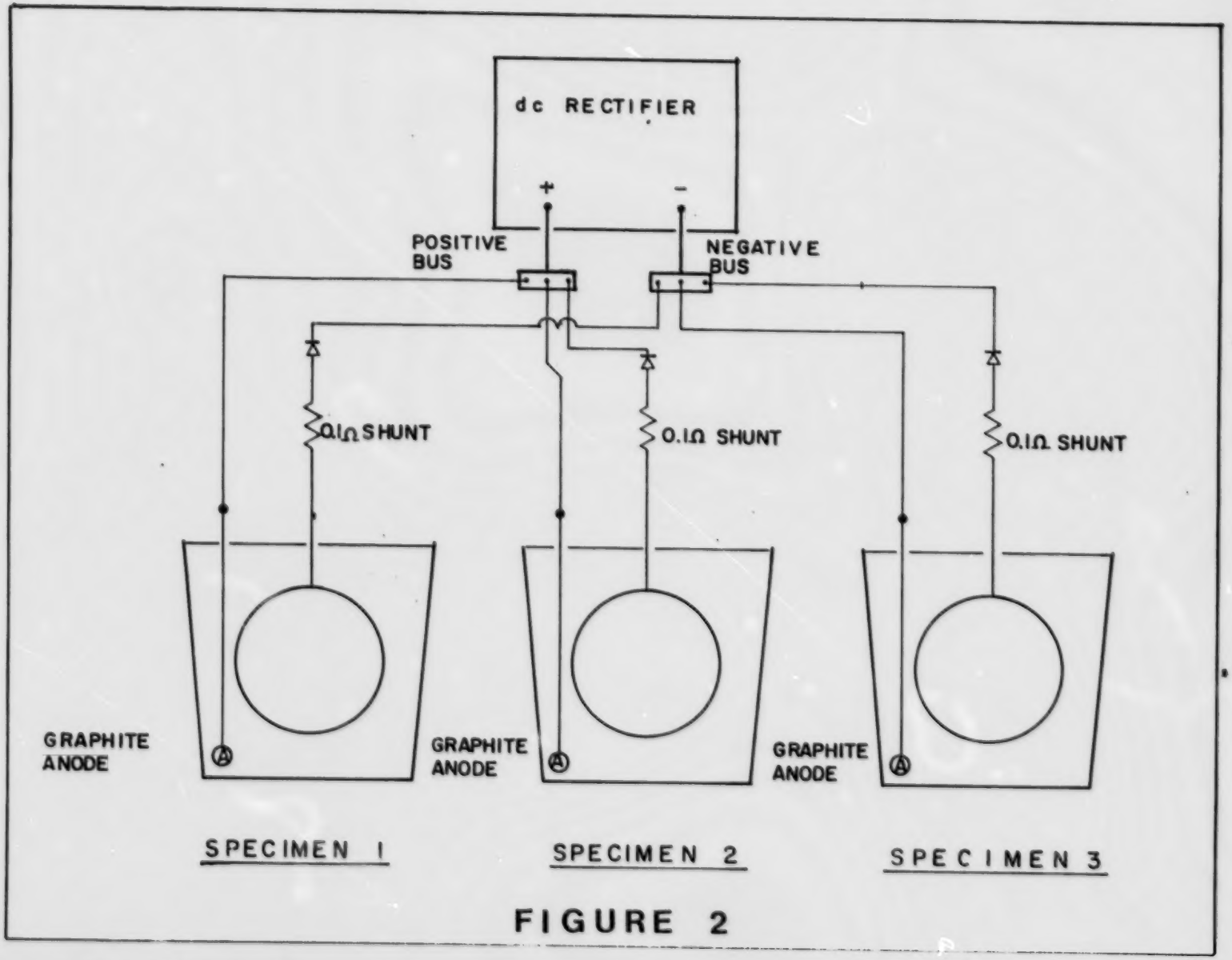

dc RECTIFIER
+
−
POSITIVE BUS
NEGATIVE BUS
0.1Ω SHUNT
0.1Ω SHUNT
0.1Ω SHUNT
GRAPHITE ANODE
GRAPHITE ANODE
GRAPHITE ANODE
SPECIMEN 1
SPECIMEN 2
SPECIMEN 3

FIGURE 2

(4.4 cont'd)

to wash in sodium bentonite, and further treatment with $Ca(OH)_2$ and $Ca(NO_2)_2$ (refer to data sheets in Appendix A for chronological record).

Specimen #1 was initially treated with a NaOH solution used to wash sodium bentonite into the sand and gravel over the tanks on October 17th, 1989. Subsequent additions involved the application of a $NaHCO_3$ solution, and further treatment with NaOH (refer to data sheets in Appendix C for chronological record).

.5 "Tank-to-soil" potentials were periodically recorded for each of the three specimens. Measurements were taken immediately before and after altering the environmental conditions for the "tank" specimens to study short-term and long-term effects. This data is included in Appendices A to F.

The procedure for recording "tank-to-soil" potentials was as follows:

i) the d.c. applied output voltage (anode to cathode) and the applied current transfer to each specimen were recorded.

ii) the applied d.c. output was interrupted to measure the reference to soil potentials for each

(4.5 cont'd)

reference electrode buried in close proximity to the surface of each tank. Using a CSE reference electrode placed over the backfill, these reference to soil potentials were used to produce "correction factors" in order to convert "IR-drop free" tank-to-graphite, and tank-to-zinc potentials to "IR-drop free" tank to CSE potentials.

iii) the rectifier was re-energized and operated uninterrupted until the current transfer to each specimen stabilized at the approximate value recorded in Step (i);

iv) the rectifier output was alternately interrupted; 20 sec. ON/10 sec. OFF to record the polarized or current-interrupted "tank-to-soil" potentials. Three potentials were recorded for each reference in the following format:

- reading d.c. ON reading 1 sec. OFF followed by reading at 10 sec. OFF. The d.c. was then reapplied.

5.0 RESULTS:

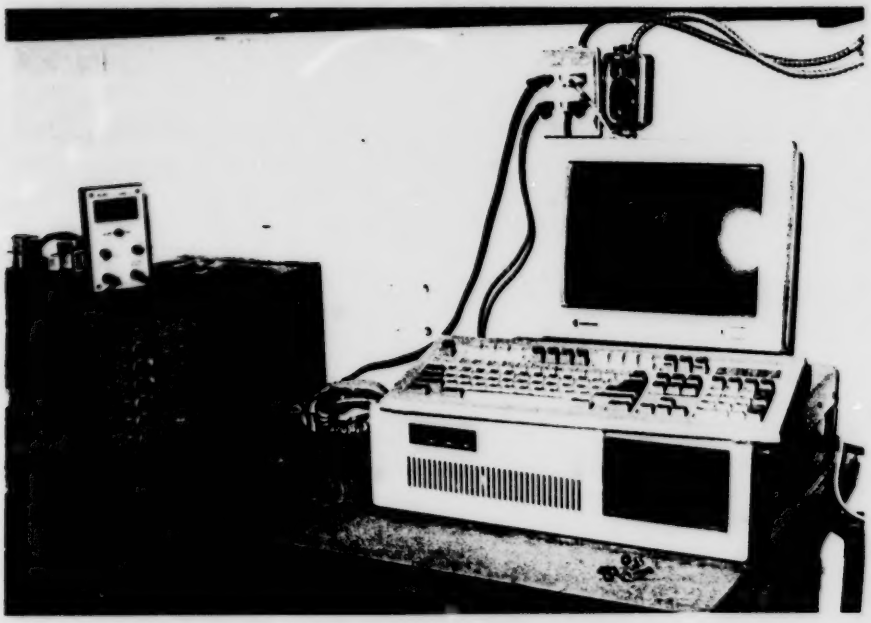
The data sheets for the Phase I Laboratory Study, "pH and Aeration Control" are contained in Appendices A to C for Specimen Nos. 1 to 3, respectively. These data sheets cover the period from September 18, 1989 to February 21, 1990.

During the period from November 28th to January 25th, the laboratory specimens were continuously subjected to CP current however, further chemical treatment and monitoring was temporarily discontinued until a revised laboratory procedure was developed and approved.

The physical investigation resumed on January 25th in accordance with the procedure dated December 31, 1989 (Appendix "G"). A diode was installed in the negative d.c. conductor for each tank specimen bonded to the common negative bus, to prevent current transfer between specimens.

Each of the specimens was subsequently transferred to the computerized data acquisition system. (Photograph #5). The depolarization graphs produced during this period are contained in Appendices D to F for Specimen Nos. 1 to 3, respectively.

Throughout this report, "tank-to-soil" measurements taken while current was interrupted are referred to as "OFF" or "polarized potentials," whereas measurements taken while current was applied are "ON" of "applied potentials."



Photograph #5 - Computerized Data Acquisition System

5.1 Specimen #1

.1 The "native" potential of this tank specimen varied from -379 mV to -383 mV (wrt Cu/CuSO4 or CSE) on September 19th, prior to the application of cathodic protection (CP).

.2 The rectified d.c. power source was energized on September 20th to apply 9.3 mA @ 2.8 V d.c. at the surface of Specimen #1. This protective current resulted in average polarized tank to soil potentials ranging from -393 mV (CSE) measured at the top surfaces of the tank to -658 mV (CSE) measured at the bottom surfaces. (Appendix "A"). This corresponds to polarization shifts ranging from approximately -16 mV at the top surface to -263 mV below the tank.

.3 The rectifier output applied at Specimen #1 was gradually increased to 62.4 mA @ 6.0 V d.c., to improve the level of cathodic polarization during the period between September 20th and October 10th, (Appendix "A").

No moisture was added directly over the specimen during this time frame, although tap water (about 5000 ohm cm) was regularly added through a funnel port to maintain the level of the water table. The soil above the water table was observed to be slowly drying out, thereby increasing its soil resistivity towards the surface.

As a result, the data recorded during this initial stabilization period was inconsistent. The tank to soil potentials were non-uniform; and were generally more

(5.1.3. cont'd)

negative at greater depth. However, the tank to surface potentials did not consistently shift in the negative direction when the rectifier output was increased. These observations also indicate that the current density is non-uniform, most of the protective current being directed at the bottom tank surfaces.

N.B. Under these circumstances, although the bottom surfaces of the tank may be considered to be cathodically protected according the NACE Criteria, these surfaces will depolarize very quickly due to charge equalization with the less polarized, more aerated top surfaces of the same structure, when the protective current is interrupted.

.4 The rectified d.c. output voltage was maintained at approximately 6.0 V d.c. during the period from October 10th to October 26th. The d.c. current output of the rectifier varied from 59.6 mA to 67.8 mA (227.48 to 258.78 mA/sq.m. OR 21.18 to 24.09 mA/sq.ft. average).

The data for Specimen #1 from September 19th to October 26th (excluding the aforementioned "stabilization period") is summarized in Table 1 (pg 41).

The sand/gravel backfill over Specimen #1 was treated with 500 ml of Ca(OH)2 solution (w/50 mg. of solute) that was evenly distributed over the surface on October 23, 1989.

TABLE 1: SPECIMEN NO. 1.

[1 SEC. "OFF" TANK POTENTIALS (@ Buried References; mV wrt CSE)]

DATE	@	BELOW TANK A1	BELOW TANK B1	ABOVE TANK A2	ABOVE TANK A3	ABOVE TANK B2	ABOVE TANK B3	TANK SIDES ZL	TANK SIDES ZR	CURRENT (mA)	COMMENTS
[1] Sep 19		-383	-382	-382	-381	-380	-381	-379	-380	0.0	Native
20		-658	-631	-400	-396	-393	-404	-466	-431	9.3 mA	@ 2.8 V d.c.
Oct 10		-1144	-666	-519	-504	-507	-544	-525	-535	62.4 mA	@ 6.1 V d.c.
12		-855	-660	-515	-502	-514	-534	-571	-508	66.8 mA	
13		-729	-665	-533	-501	-510	-532	-509	-538	67.8 mA	
17		-718	-752	-513	-496	-504	-540	-524	-518	67.6 mA	
[2] 23	a.m.	-596	-745	-495	-484	-485	-516	-491	-487	59.6 mA	
[3] 23	p.m.	-768	-626	-536	-533	-542	-548	-569	-583	61.8 mA	10% Ca(OH)2
24		-705	-663	-542	-540	-552	-567	-582	-571	64.1 mA	
26		-667	-627	-537	-536	-548	-564	-560	-562	62.7 mA	
POTENTIAL SHIFTS:											
[2]-[1]		-213	-363	-113	-103	-105	-135	-112	-107	59.6 mA	
[3]-[1]		-385	-244	-154	-152	-162	-167	-190	-203	61.8 mA	
[3]-[2]		-172	+119	-41	-49	-57	-32	-78	-96	2.2 mA	

gr-canmet1

(5.1.4. cont'd)

This treatment did not cause a dramatic change in the current output. A comparison of the various average polarized "tank-to-soil" potentials is as follows:

Average "Tank-to-Soil" Potentials (mV wrt Cu/CuSO4).

References	Before [Oct. 10th to Oct. 23rd a.m.]	After [Oct. 23rd p.m. to Oct. 26th]
A1 (Gravel-bottom)	-808	-713
B1 (Sand-bottom)	-698	-639
A2/A3 (Gravel-top)	-506	-537
B2/B3 (Sand-top)	-519	-554

These average polarized potential negative shifts indicate that treatment with the Ca(OH)2 solution improved the polarization shift on the top surfaces of the tank, while some loss of polarization occurred at the bottom surfaces of the tank.

This may indicate that this treatment of the soil caused a redistribution of the cathodic protection current with a greater proportion of the current reaching the top surfaces of the tank.

(5.1.4. cont'd)

This hypothesis is not supported however, by a comparison of the magnitude of "IR drops" measured while current was applied at the references located directly over the "tank" immediately before and after the application of the Ca(OH)2 solution (Appendix "A").

"IR" Drop Values (mV)

References	Oct. 23rd, a.m.			Oct. 23rd p.m.		
	ON	OFF	'IR'	ON	OFF	'IR'
A2 (Gravel)	555	495	60 mV	537	536	1 mV
A3 (Gravel)	493	484	9 mV	534	533	1 mV
B2 (Sand)	493	485	8 mV	561	542	19 mV
B3 (Sand)	622	516	106 mV	611	548	63 mV

This comparison demonstrates that the magnitude of the "IR Drop" measured on top of this tank while current was applied reduced after the application of the Ca(OH)2 solution. This could be a consequence of a reduction of current density in this area, and/or the soil resistivity; as mentioned

Table 2: SPECIMEN NO. 1.

[1 SEC. "OFF" TANK POTENTIALS (@ Buried References; mV wrt CSE)]

DATE		@	BELOW TANK A1	BELOW TANK B1	ABOVE TANK A2	ABOVE TANK A3	ABOVE TANK B2	ABOVE TANK B3	TANK SIDES ZL	TANK SIDES ZR	CURRENT (mA)	COMMENTS
[1] Sep	19		-383	-382	-382	-381	-380	-381	-379	-380	0.0	Native
Oct	27	a.m.	-801	-721	-549	-547	-564	-609	-624	-630	124.8 mA	@ 10.1 V d.c.
	27	p.m.	-796	-715	-562	-560	-575	-613	-610	-605	125.2 mA	500 ml H20
	31		-765	-751	-550	-541	-548	-582	-628	-620	109.2 mA	
Nov	3		-940	-1021	-550	-525	-533	-608	-663	-578	109.6 mA	
[2]	7		-700	-815	-522	-510	-521	-567	-628	-550	96.6 mA	
[3]	8		-637	-866	-540	-540	-549	-583	-629	-578	104.8 mA	500 ml H20
	9		-679	-824	-571	-574	-579	-590	-654	-602	148.6 mA	
	10		-651	-795	-579	-577	-583	-596	-693	-582	130.8 mA	
	13		-728	-947	-579	-579	-588	-589	-668	-567	109.5 mA	
	15		-689	-918	-575	-575	-580	-598	-622	-509	108.9 mA	
	21		-629	-934	-569	-570	-574	-606	-670	-589	106.9 mA	
	24		-704	-979	-566	-566	-571	-607	-682	-670	112.4 mA	
[4]	28	a.m.	-779	-1048	-565	-566	-571	-603	-600	-574	116.1 mA	
[5]	28	p.m.	-780	-1012	-542	-547	-557	-586	-646	-634	122.9 mA	500 ml NaHC03
POTENTIAL SHIFTS:												
[2]-[1]			-317	-433	-140	-129	-141	-186	-249	-170	96.6 mA	
[3]-[1]			-254	-484	-158	-159	-169	-202	-250	-198	104.8 mA	
[3]-[2]			+63	-51	-18	-30	-28	-16	-1	-28	8.2 mA	
[4]-[1]			-396	-666	-183	-185	-191	-222	-221	-194	116.1 mA	
[5]-[4]			-1	+36	+23	+19	+14	+17	-46	-60	6.8 mA	

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(5.1.4 cont'd)

previously however, this treatment did not cause a dramatic change in the total current applied at the surface of this specimen.

.5 The rectifier's output voltage was increased prior to recording data on October 27, 1989. The voltage was maintained at approximately 10.1 V d.c. during the period from October 27 to November 28th, 1989. The current output to Specimen #1 varied from 96.6 mA d.c. to 148.6 mA d.c. (368.70 to 567.18 mA/sq.m. OR 34.33 to 52.81 mA/sq.ft. avg.) as various solutions were added to the soil. This data is summarized in Table 2 (pg. 44).

The immediate effect of the change was an increase in the current output from 62.7 mA d.c. to 124.8 mA d.c. The corresponding "tank-to-soil" potentials shifted negative as expected. However, the level of polarization remained non-uniform despite the addition of the Ca(OH)2 solution on October 23, and the increase in the d.c. output of the rectifier (refer to October 27, 1989 a.m. - Appendix A).

Subsequent to this set of data being recorded, 500 ml of distilled water were added directly over Specimen #1; the October 27 p.m. data shows that the resulting changes in current output and "tank-to-soil" potentials were very minor.

(5.1.5 cont'd)

In the period immediately following these changes the "tank-to-soil" potentials remained very stable. However, a significant observation, of potentials, directly below the tank, was made on November 3, 1989. A significant negative shift to -940 mV @ A1 and -1021 mV @ B1 (1 sec. "OFF" wrt. CSE) occurred on the bottom surfaces of this specimen for no apparent reason.

N.B. In 10 seconds these potentials depolarized the -532 mV @ A1 and -603 mV @ B1 (wrt. CSE). The "tanks" tend to depolarize to a uniform potential.

By November 7th, the 1 s. "OFF" potentials had declined to -700 mV @ A1 and -815 mV @ B1. Another observation was noted; after this occurrence, the bottom surfaces of Specimen #1 are consistently more polarized on the sand side (@ B1) versus the gravel side (A1).

The sand/gravel backfill over Specimen #1 was again treated with chemical solutions prior to the set of readings on November 8th. 250 ml of $NaHCO_3$ solution (with 25 mg. of solute) were used to wash 40 mg of sodium bentonite into the end of the "tank", backfilled with gravel. An additional 250 ml of $NaHCO_3$ solution were used to treat the sand end.

Prior to this chemical treatment, both the d.c. output and the corresponding "tank-to-soil" potentials had been

(5.1.5. cont'd)

steadily declining. The addition of the NaHCO3 solution caused a significant increase in current two days later, with a corresponding negative shift of the tank's surface potentials.

Specimen #1 was periodically monitored to November 28th. The "tank" was still not uniformly cathodically protected. Although the top surfaces of the tank had been shifted almost 200 mV from the native potentials, the level of protection was still far short of the -850 mV (CSE) NACE criteria.

These results were unacceptable given the extremely high current densities that were being employed. Therefore the results to data were evaluated and a new course of action was plotted.

.6 The rectifiers output voltage was increased to 12 V d.c., on January 25th, 1990, to compensate for the installed diode. The voltage was maintained at approximately 12 V d.c. during the period from January 25th to February 14th, 1990. The current output to Specimen #1 varied significantly during this period. This data is summarized in Table 3 (pg. 48).

TABLE 3: SPECIMEN NO. 1.

[1 SEC "OFF" TANK POTENTIALS (@ Buried References; mV wrt CSE)]

DATE	@	BELOW TANK A1	BELOW TANK B1	ABOVE TANK A2	ABOVE TANK A3	ABOVE TANK B2	ABOVE TANK B3	TANK SIDES ZL	TANK SIDES ZR	CURRENT (mA)	COMMENTS
[1] Sep 19		-383	-382	-382	-381	-380	-381	-379	-380	0.0	Native
Jan 25		-563	-563	-472	-473	-475	-483	-480	-423	57.7 mA	@ 12 V d.c.
Feb 1		-555	-490	-468	-468	-467	-469	-437	-467	34.9 mA	
5		-520	-508	-478	-477	-476	-481	-479	-522	26.6 mA	
7	a.m.	-505	-501	-466	-465	-464	-466	-478	-447	46.0 mA	
7	p.m.(1)	-531	-569	-465	-465	-465	-472	-482	-447	83.7	"Tannin" Plate
7	p.m.(2)	-427	-465	-463	-462	-456	-454	-470	-443	34.3 mA	
[2] 8	a.m.	-531	-485	-448	-447	-447	-447	-454	-451	33.3 mA	
8	p.m.	-1182	-850	-676	-670	-684	-701	-846	-840	1180.0 mA	1 L Ca(NO2)2 & 500 ml Ca(OH)2
9		-810	-867	-718	-719	-739	-802	-788	-740	248.0 mA	
12		-694	-691	-699	-697	-694	-692	-693	-692	5.0 mA	
[3] 14		-656	-657	-660	-656	-655	-655	-656	-658	4.5 mA	
POTENTIAL SHIFTS:											
[2]-[1]		-148	-103	-66	-81	-67	-66	-75	-71	33.3 mA	
[3]-[1]		-273	-275	-278	-275	-275	-274	-277	-278	4.5 mA	
[3]-[2]		-125	-172	-212	-209	-208	-208	-202	-207	-28.8 mA	

(5.1.6 cont'd)

On February 7th, a portion of Specimen #1 was excavated to allow a steel plate to be buried in the sand. This plate had an exposed surface area of 10,000 sq. mm of rusted steel, that was treated with tannin.

The immediate effect of introducing this plate into the CP system was a dramatic increase in the d.c. transfer to Specimen #1. The d.c. transfer increased from 46.0 mA to 83.7 mA d.c., with only minor changes in polarization levels. This was only a short term effect; the current output declined to 34.3 mA within two (2) hours. The net effect of this alteration was a significant deterioration in "tank-to-soil" potentials on the bottom surfaces of this tank. Specimen #1 was now uniformly poorly polarized.

On February 8th, 1990 further chemical treatment of the soil backfill was conducted. One litre of commercially available, premixed calcium nitrite (Ca[NO2]2) solution was evenly distributed over this specimen. This was quickly followed by 500 ml of Ca(OH)2 solution (w/25 mg of solute) that were added to this specimen.

This application produced immediate and significant results. The current output to Specimen #1 increased from 33.3 mA to 1180 mA . A significant negative shift in the corresponding "tank-to-soil" potentials was also observed. (February 8th p.m. - Appendix "A"). The "tank-to-soil" potentials on the top surfaces of this model had been shifted to an average of -745 mV (CSE); i.e., -365 mV wrt. native potentials.

(5.1.6 cont'd)

The polarization characteristics of this specimen were recorded again within 24 hours of the chemical treatment. The current transfer to this specimen had declined to 248 mA; still too high @ 946.56 mA/sq.m., (88.13 mA/sq.ft.)

Similarly to the previous chemical application of Ca(OH)2 solution on October 23, 1989 the polarization shift on the top surfaces of the tank continued to improve, while some loss of polarization occurred at the bottom surfaces of the tank. Again, this may indicate that this treatment of the soil caused a redistribution of the cathodic protection current with a greater proportion of the current reaching the top surfaces of the tank.

By February 14th, 1990, d.c. output of the rectifier to Specimen #1 had declined to 4.5 mA @ 11.6 V d.c. Furthermore the "tank" was now uniformly protected at an average "tank-to-soil" potential of -657 mV (CSE); a uniform shift of -276 mV from the "native potentials."

In addition to the uniform level of polarization, the chemical treatment has also produced a very slow rate of depolarization of the "tank-to-soil" potentials. (February 14th, 1990 - Appendix "A").

(5.1.7. cont'd)

Therefore the treatment with 1 litre of $Ca(NO2)2$ solution followed by 500 ml of $Ca(OH)2$ solution produced these results.

a) a uniformly polarized structure;
b) a slow rate of depolarization; and
c) a significantly reduced current output (17.18 mA/sq.m. OR 1.60 mA/sq.ft.).

Further refinements were required to attempt to satisfy the -850 mV (CSE) polarized potential criteria.

.7 Further efforts were directed towards maintaining the aforementioned positive effects, while reducing the rectifier's output voltage and achieving uniform polarized potential of -850 mV (CSE).

On February 16th, all four graphite references on top and references B1 were temporarily connected as impressed current anodes. Shortly thereafter the top references were disconnected from the rectifier's positive bus (to be restored as references) and Reference B1 remained as the fifth graphite impressed current anode. (Appendix "A").

With B1 used as an anode, the output of the anode bed was 3.4 mA @ 1.7 V d.c. When this anode, B1, was disconnected the output of the anode bed declined to 0.9 mA @ 1.7 V d.c.

(5.1.7. cont'd)

On February 18th, reference B1 was restored as a reference, and an additional graphite anode was installed above the "tank." Subsequent to this change, the soil was treated with the following chemical solutions:

i) 500 ml of saturated Ca(OH)2 solution;
ii) 200 ml of Ca(NO2)2 solution; and
iii) and additional 300 ml of saturated Ca(OH)2 solution.

Subsequent to this treatment, the newly installed top anode was supplying virtually all of the current; i.e., the original four anodes were producing negligible current.

In this situation, with the soil around the tanks saturated with the various chemical solutions, and with an anode over the top of the "tank" specimen, the top surfaces of the "tank" were better polarized (average -796 mV wrt. CSE), than the bottom surfaces (average -765 mV wrt. CSE), (February 19th p.m. - Appendix "A"). Please note that the top surfaces were quickly depolarizing at this time, due to charge equalization with the less polarized bottom surfaces of the same structure.

On February 20th, 1990, additional chemical solutions were added to the soil over Specimen #1. The soil pH was checked and recorded at various locations over the "tank." The

(5.1.7 cont'd)

chemical solutions and changes in average pH were as follows:

a) BEFORE pH = 9.37
b) 500 ml of $Ca(NO_2)_2$ solution pH = 10.25
c) 1000 ml of saturated $Ca(OH)_2$ solution pH = 11.75
d) 500 ml of saturated $CaSiO_3$ solution pH = 10.75

On February 21st, 1990 an additional 250 ml of saturated $Ca(OH)_2$ solution, and 500 ml of saturated calcium silicate were added to Specimen #1.

.8 The impressed current anodes and negative connections for this "tank" were subsequently transferred to the d.c. power source on a custom designed, computerized data acquisition system. The six graphite references and a portable CSE were connected to the computerized instrumentation package.

This instrumentation was designed to simultaneously monitor "tank-to-soil" potentials at all seven references, at 110 ms intervals. This allowed very accurate plotting of the depolarization curves (Appendix "D").

Specimen #1 was monitored with the computerized data acquisition system from February 27th, to March 2, 1990. The resulting "depolarization curves" are shown in Appendix "D".

(5.1.8 cont'd)

The total time span for the graphs is 11.66 seconds. The initial 330 ms of data were recorded while the current was applied. Following this, the current was interrupted and the instrumentation recorded 11 seconds of "tank-to-soil" potentials at 110 ms intervals. The protective current was restored after this 11 second interrupted period.

These "tank-to-soil" potentials wrt the graphite references were converted to Cu/CuSO4 readings. The graphs are grouped according to reference location (as noted), and are arranged in chronological order. The rectified d.c. outputs to Specimen #1 were altered as follows:

February 27, 1990:	38 mA @ 982 mV d.c.
February 28, 1990:	38.1 mA @ 993 mV d.c.
March 1, 1990:	24.9 mA @ 691 mV d.c.
March 2, 1990 (a.m.):	15.1 mA @ 455 mV d.c.
March 2, 1990 (p.m.):	15.1 mA @ 455 mV d.c.

Some general observations of the graphs in Appendix "D" are as follows:

i) with the exception of some instrumentation interference ($\pm$ 6 mV), the graphs are very flat; i.e., very little depolarization was observed during the 11 second period of current interruption;

(5.1.8 cont'd)

ii) as the rectifier output was reduced from 38 mV d.c. to 15.1 mA d.c. the polarized potentials uniformly declined from approximately -850 mV (CSE) to -740 mV (CSE); and

iii) the depolarization curves for the top references (Graphite Refs. A2/A3/B2/B3 and Portable CSE) clearly indicate the moment of current interruption, as the "IR-drop" component of the "tank-to-soil" potentials is removed; the lack of a clearly defined "IR-drop" at the reference locations below the tank (particularly @ A1) may be an indication of a reduced current density at these surfaces.

iv) the output of the constant current rectifier on March 2nd, varied as follows, as the configuration of the impressed current groundbed was changed:

a) 15.1 mA @ 455 mV d.c. (w/top anodes);
b) 15.1 mA @ 31.6 V d.c. (w/o top anodes; bottom anodes only).

5.2 Speciman #2 "Control Specimen"

.1 The "native" potential of this tank specimen varied from -406 mV to -423 mV (wrt. CSE) on September 19th, prior to the application of cathodic protection (CP).

.2 The rectified d.c. power source was energized on September 20th to apply 9.7 mA @ 2.8 V d.c. at the surface of Specimen #2. This protective current resulted in average polarized "tank-to-soil" potentials ranging from -436 mV (CSE) measured at the top surfaces of the tank to -819 mV (CSE) measured at the bottom surfaces. (Appendix "B") This corresponds to polarization shifts ranging from approximately -24 mV at the top surfaces to -408 mV below the tank.

.3 The rectifier output applied at Specimen #2 was gradually increased to 62.1 mA @ 6.0 V d.c. to improve the level of cathodic polarization during the period between September 20th and October 10th (Appendix "B").

No moisture was added directly over the specimen during this time frame, although tap water (about 5000 ohm cm) was regularly added through a funnel port to maintain the level of the water table. As in the other specimens, the backfill over the "Control" was observed to be slowly drying out, thereby increasing its soil resistivity towards the surface.

The data recorded during the initial stabilization period was inconsistent; similar to the other specimens. The tank

(5.2.3 cont'd)

to soil potentials were non-uniform; these polarized potentials were generally more negative at greater depth. However, the tank-to-soil potentials at the surface did not consistently shift in the negative direction when the rectifier output was increased. Again, these observations indicate that the current density is non-uniform, most of the protective current being directed at the bottom of the tank surfaces.

N.B. The bottom surfaces depolarized very quickly due to charge equalization with the less polarized, more aerated top surfaced of the same structure when the protective current was interrupted.

.4 The rectified d.c. output voltage was maintained at approximately 6.0 V d.c. during the period from October 10th to October 26th. The d.c. current output of the rectifier to Specimen #2 varied from 62.1 mA to 68.4 mA d.c. (237.02 to 261.07 mA/sq.m., 22.07 to 24.31 mA/sq.ft. average), as conditions were altered.

The data for Specimen #2 from September 19th to October 26th (excluding the aforementioned "stabilization period") is summarized in Table 4 (pg. 58).

Whenever the backfill of either Specimen #1 or #3 were treated with chemical solutions, the backfill over the "Control" was subjected to equal volume of distilled water evenly distributed over the surface.

TABLE 4: SPECIMEN NO. 2, "CONTROL",

[1 SEC "OFF" TANK POTENTIALS (@ Buried References; mV wrt CSE)]

DATE	@	BELOW TANK A1	BELOW TANK B1	ABOVE TANK A2	ABOVE TANK A3	ABOVE TANK B2	ABOVE TANK B3	TANK SIDES ZL	TANK SIDES ZR	CURRENT (mA)	COMMENTS
[1] Sep 19		-412	-410	-429	-406	-408	-406	-407	-408	0.0	Native
20		-793	-845	-474	-426	-417	-425	-487	-489	9.7 mA @ 2.8 V d.c.	
Oct 10		-863	-677	-474	-478	-480	-534	-497	-532	62.1 mA @ 6.1 V d.c.	
12		-785	-622	-481	-473	-481	-517	-535	-512	65.0 mA	
13		-732	-650	-484	-483	-492	-518	-444	-514	67.1 mA	500 ml H20
17		-836	-611	-518	-500	-502	-527	-549	-550	68.4 mA	
[2] 23	a.m.	-796	-616	-472	-459	-470	-499	-519	-481	64.0 mA	
[3] 23	p.m.	-717	-545	-468	-466	-468	-495	-518	-495	65.3 mA	250 ml H20
24		-736	-578	-500	-484	-475	-496	-523	-518	65.7 mA	
26		-689	-607	-493	-481	-483	-504	-504	-492	64.1 mA	
POTENTIAL SHIFTS:											
[2]-[1]		-384	-206	-43	-53	-62	-93	-112	-73	64.0 mA	
[3]-[1]		-305	-135	-39	-60	-60	-89	-111	-87	65.3 mA	
[3]-[2]		+79	+71	+4	-7	+2	+4	+1	-14	1.3 mA	

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(5.2.4 cont'd)

The mere addition of moisture to the backfill did not appear to have a significant effect on polarized potentials (refer to Table 4).

A total of 750 ml of distilled water was applied over Specimen #2 between October 12th and October 23rd. The current output on October 12th was 65.0 mA and 65.3 mA d.c. on October 23rd. The corresponding "tank-to-soil" potentials compare as follows:

Average "Tank-to-Soil" Potentials (mV wrt Cu/CuSO4).

References	Before October 12, 1990	After October 23, 1990
A1 (Gravel-bottom)	-785	-717
B1 (Sand-bottom)	-622	-545
A2/A3 (Gravel-top)	-477	-467
B2/B3 (Sand-top)	-499	-481

This data indicated that treatment with distilled water did not improve polarization levels; although the rectifier output remained relatively stable, the polarized potentials actually declined during this period.

(5.2.4 cont'd)

There is no indication that the distilled water caused a shift in the distribution of the protective current from the bottom surfaces to the top surfaces; the absolute magnitude of loss in polarization is greater on the bottom surfaces than on the top.

The rectifiers output voltage was increased prior to recording data on October 27th, 1989. The voltage was maintained at approximately 10.1 V d.c. during the period from October 27th to November 28th, 1989. The current output to Specimen #2 varied from 78.0 mA d.c. to 128.8 mA d.c. (297.71 to 491.60 mA/sq.m. OR 27.72 to 45.77 mA/sq. ft. average). This data is summarized in Table 5 (pg. 61).

The immediate effect of the change in output voltage was an increase in the current output from 64.1 mA to 128.8 mA d.c. The "tank-to-soil" potentials shifted negative as a result of this doubling in the protective current directed at the control specimen's surface.

In general, the polarized potentials continued to decline over time as the current transfer declined from 128.8 mA d.c. on October 27th to 94.2 mA d.c. on November 7th; however this decline was not absolutely consistent. Thenceforward this rectifier output and the polarized potentials seemed to vary up and down, with no discernable correlation between them, or the addition of the distilled water.

TABLE 5: SPECIMEN NO. 2, "CONTROL",

[1 SEC "OFF" TANK POTENTIALS (@ Buried References; mV wrt CSE)]

DATE	@	BELOW TANK A1	BELOW TANK B1	ABOVE TANK A2	ABOVE TANK A3	ABOVE TANK B2	ABOVE TANK B3	TANK SIDES ZL	TANK SIDES ZR	CURRENT (mA)	COMMENTS
[1] Sep 19		-412	-410	-429	-406	-408	-406	-407	-408	0.0	Native
Oct 27	a.m.	-945	-728	-520	-489	-493	-557	-563	-532	128.8 mA	@ 10.1 V d.c.
27	p.m.	-911	-659	-530	-510	-509	-550	-550	-529	128.6 mA	500 ml H20
31		-730	-710	-545	-509	-511	-537	-529	-517	104.2 mA	
Nov 3		-1009	-843	-602	-506	-502	-584	-630	-522	99.3 mA	
[2] 7		-779	-815	-553	-476	-475	-517	-532	-482	94.2 mA	
[3] 8		-838	-681	-514	-494	-489	-518	-519	-501	98.1 mA	500 ml H20
9		-814	-685	-524	-488	-481	-513	-546	-492	91.8 mA	
10		-746	-679	-524	-484	-479	-514	-518	-492	88.4 mA	
13		-835	-773	-550	-484	-485	-522	-547	-505	89.8 mA	
15		-818	-777	-509	-481	-480	-529	-558	-512	95.9 mA	
21		-709	-756	-486	-473	-477	-517	-516	-483	79.4 mA	
24		-919	-892	-514	-479	-481	-535	-544	-508	80.4 mA	
[4] 28	a.m.	-807	-740	-481	-470	-473	-514	-530	-492	78.0 mA	
[5] 28	p.m.	-881	-826	-482	-476	-480	-525	-540	-506	79.8 mA	500 ml H20
POTENTIAL SHIFTS:											
[2]-[1]		-367	-405	-124	-70	-67	-111	-125	-74	94.2 mA	
[3]-[1]		-426	-271	-85	-88	-81	-112	-112	-93	98.1 mA	
[3]-[2]		-59	+134	+39	-18	-14	-1	+13	-19	3.9 mA	
[4]-[1]		-395	-330	-52	-64	-65	-108	-123	-84	78.0 mA	
[5]-[4]		-74	-86	-1	-6	-7	-11	-10	-14	1.8 mA	

(5.2.6. cont'd)

.6 The rectifier's output voltage was increased to 12 V d.c. on January 25th, 1990 to compensate for the installed diode. The voltage was maintained at 12 V d.c. during the period from January 25th to February 14th, 1990. The current output to Specimen #2 varied from 69.0 mV d.c. to 89.2 mA d.c. This data is summarized in Table 6 (pg. 63).

The "tank-to-soil" potentials for this specimen were not consistent during this period. The level of polarization remained non-uniform despite all of the distilled water that had been added, and the increase in the d.c. output of the rectifier (refer to February 1st, 1990 - Appendix "B").

On February 8th an additional 1.5 l of distilled water were added to the "Control Specimen." The rectifier output changed from 73.5 mA @ 118 V d.c. to 71.7 mA @ 11.4 V d.c. immediately after the addition of the water. This output changed further by February 14th to 74.9 mA @ 11.6 mV d.c. The corresponding "tank-to-soil" potentials compare as follows:

Average "Tank-to-Soil" Potentials (mV wrt. Cu/Cu/SO4)

References	Before February 8th a.m.	After February 14, 1990
A1 (Gravel bottom)	-958	-920
B1 (Sand-bottom)	-789	-708
A2/A3 (Gravel-top)	-473	-524
B2/B3 (Sand-top)	-485	-542

TABLE 6: SPECIMEN NO. 2, "CONTROL",

[1 SEC "OFF" TANK POTENTIALS (@ Buried References; mV wrt CSE)]

DATE		BELOW TANK @ A1	BELOW TANK B1	ABOVE TANK A2	ABOVE TANK A3	ABOVE TANK B2	ABOVE TANK B3	TANK SIDES ZL	TANK SIDES ZR	CURRENT (mA)	COMMENTS
[1]Sep 19		-412	-410	-429	-406	-408	-406	-407	-408	0.0	Native
Jan 25		-789	-869	--	-451	-459	-504	-535	-510	88.2 mA	@ 12 V d.c.
Feb 1		-833	-1227	--	-451	-459	-526	-664	-603	89.2 mA	
5		-1415(?)	-783	-493	-488	-487	-525	-536	-510	82.9 mA	
7	a.m.	-940	-1002	-489	-475	-479	-509	-530	-496	70.0 mA	
7	p.m.	-877	-895	-478	-473	-479	-508	-527	-485	69.0 mA	
[2] 8	a.m.	-958	-789	-475	-471	-475	-495	-561	-496	73.5 mA	
8	p.m.	-1198	-839	-529	-507	-507	-527	-538	-514	71.7 mA	1.5 l H20
9		-835	-695	-550	-518	-521	-552	-591	-541	73.3 mA	
12		-920	-697	-531	-523	-527	-558	-561	-532	75.2 mA	
[3] 14		-920	-708	-526	-523	-528	-555	-588	-547	74.9 mA	
POTENTIAL SHIFTS:											
[2]-[1]		-546	-379	-46	-65	-67	-89	-154	-88	73.5 mA	
[3]-[1]		-508	-298	-97	-117	-120	-149	-181	-139	74.9 mA	
[3]-[2]		+38	+81	-51	-52	-53	-60	-27	-51	1.4 mA	

(5.2.6 cont'd)

Over this period of time polarization shift of approximately 50 mV was observed on the top surfaces, while some loss of polarization occurred at the bottom surfaces of the tank.

The "Control-Specimen" exhibited most polarization shift on the bottom surfaces backfilled in gravel. The top surfaces had only been shifted approximately 120 mV from "native" potentials and the side backfilled with sand was slightly better polarized than the gravel side.

.7 Specimen #2 was temporarily depolarized on February 17th, and 18th when a graphite reference was inadvertently bonded to the tank. Subsequent to this Reference A2 was changed into a graphite anode over the top of this tank, and the rectifier's output was drastically reduced to 4.1 mA @ 2.8 V d.c. These changes resulted in a general decline in polarization levels on the bottom tank surfaces, (February 20, 1990 a.m. - Appendix "B"). The level of polarization around the perimeter of the tank became more uniform - the "tank" was now uniformly poorly protected.

Immediately following this set of readings, an additional 1.5 L. of tapwater were added over the "Control Specimen." In this case the tapwater (as opposed to the previous distilled water) did cause an immediate uniform shift in the polarized potentials of the tank surfaces of approximately 60 mV. The resulting polarized potentials ranged from -627 mV to -657 mV (CSE).

(5.2.7 cont'd)

The average pH on the surface of the backfill was approximately 7.5 prior to the addition of the tapwater. The average pH temporarily increased to 8.0 after the addition of the water before declining back to 7.125 within 24 hours.

By February 21st the range of polarized potentials had changed to a range of -656 mV to -727 mV (CSE), and the d.c. current output to the "Control Specimen" had increased to 4.6 mA @ 2.3 V d.c., with two anodes installed over the tank.

The resulting cathodic protection levels were still not uniform at this reduced current output (1.63 mA/sq.ft.). The rate of depolarization had been improved somewhat by the additional tapwater.

.8 The impressed current anodes and negative connections for this tank were subsequently transferred to the d.c. power source on the custom designed, computerized data acquisition system. This six graphite references and a portable CSE were connected to the computerized instrumentation package.

Detailed depolarization curves for Specimen #2 were produced by this instrumentation, (Appendix "E").

(5.2.9. cont'd)

.9 Specimen #2 was monitored with the computerized data acquisition system on March 8th to March 9th, 1990. The resulting "depolarization curves" are shown in Appendix "E".

March 8, 1990 a.m. - 32.8 mA @ 5.3 V d.c.
March 8, 1990 p.m. - 32.4 mA @ 5.6 V d.c.
March 9, 1990 a.m. - 24.9 mA @ 4.3 V d.c.
March 9, 1990 p.m. - 15.0 mA @ 3.4 V d.c.

Some general observations of the graph in Appendix "E" are as follows:"

i) the polarized potentials at the various locations on the tank surface are non-uniform; as the rectifier output was reduced from 32.8 mA d.c. to 15.0 mA d.c. these "tank-to-soil" potentials declined as follows:

"Tank-to-Soil" Potentials

References	Range of Polarized Potentials
A1 (Gravel bottom)	-925 mV to -810 mV (CSE)
B1 (Sand-bottom)	-800 mV to -720 mV (CSE)
A2/A3 (Gravel-top)	-800 mV to -720 mV (CSE)
B2/B3 (Sand-top)	-870 mV to -760 mV (CSE)

(5.2.9 cont'd)

Please note that in this "Control Specimen":

a) the bottom surfaces on the gravel-backfilled end are better protected than those on the sand-backfilled end;

b) the top aerated surfaces on the sand-backfilled end are better protected than those on the bottom surfaces;

c) the "tank-to-soil" potentials at Reference A3 were inconsistent; they actually improved as the rectifier output was reduced.

ii) The depolarization curves are not absolutely flat; a fairly significant magnitude of depolarization was observed on this tank.

iii) The output of the constant current rectifier on March 9th p.m. varied as follows, as the configuration of the impressed current groundbed was changed;

a) 15.0 mA @ 3.4 V d.c (w/top anodes).

b) 15.0 mA @ 4.8 V d.c. (w/o top anodes; bottom anodes only).

5.3 Specimen #3

.1 The "native" potential of this tank specimen varied from -428 mV to -434 mV (wrt. Cu/CuSO4 or CSE) on September 19th, prior to the application of cathodic protection (CP).

.2 The rectifier d.c. power source was energized on September 20th to apply 8.1 mA @ 2.8 V d.c. at the surface of Specimen #3. This protective current resulted in average polarized tank to soil potentials ranging from -453 mV (CSE) measured at the top surfaces of the tank to -923 mV (CSE) measured at the bottom surfaces, (Appendix "C"). This corresponds to polarization shifts ranging from approximately -25 mV at the top surface to -491 mV below the tank.

.3 The rectifier output applied at Specimen #1 was gradually increased to 50.7 mA @ 6.0 V d.c., to improve the level of cathodic polarization during the period between September 20th and October 10th, (Appendix "C").

No moisture was added directly over the specimen during this time frame, although tap water (about 5000 ohm cm) was regularly added through a funnel port to maintain the level of the water table. The soil above the water table was observed to be slowly drying out, thereby increasing its soil resistivity towards the surface.

The data recorded during this initial stabilization period was inconsistent; similar to the other specimens. The tank to soil potentials were non-uniform; and were generally more

(5.3.3 cont'd)

negative at greater depth. However, the tank surface potentials did not consistently shift in the negative direction when the rectifier output was increased. Again these observations indicate that the current density is non-uniform, most of the protective current being directed at the bottom tank surfaces.

N.B. The bottom surfaces depolarized very quickly due to charge equalization with the less polarized, more aerated top surfaces of the same structure, when the protective current was interrupted.

The rectified d.c. output voltage was maintained at approximately 6.0 V d.c. during the period from October 10th to October 26th. The d.c. current output of the rectifier to Specimen #3 varied from 50.7 mA to 108.1 mA (193.51 to 412.60 mA/sq.m., OR 18.01 to 38.42 mA/sq.ft. average) as electrochemical conditions were altered.

The data for Specimen #3 from September 19th to October 26th (excluding the aforementioned "stabilization period")is summarized in Table 7 (pg. 70).

The sand/gravel backfill over Specimen #3 was treated with 500 ml of NaOH solution (w/50 mg. of solute) that was evenly distributed over the surface to wash 81 mg of sodium bentonite into the sand and gravel over the "tank" on October 13th, 1989.

TABLE 7: SPECIMEN NO. 3,

[1 SEC "OFF" TANK POTENTIALS (@ Buried References; mV wrt CSE)]

DATE	@	BELOW TANK A1	BELOW TANK B1	ABOVE TANK A2	ABOVE TANK A3	ABOVE TANK B2	ABOVE TANK B3	TANK SIDES ZL	TANK SIDES ZR	CURRENT (mA)	COMMENTS
[1] Sep 19		-432	-431	-428	-429	-428	-428	-434	-429	0.0	Native
Oct 27	a.m.	-820	-877	-600	-599	-600	-603	-633	-632	97.1 mA	@ 10.1 V d.c.
27	p.m.	-814	-833	-598	-598	-600	-603	-624	-631	101.5 mA	500 ml H2O
31		-811	-787	-572	-571	-573	-578	-603	-610	116.5 m	
Nov 3		-827	-772	-584	-549	-551	-556	-627	-748	106.3 mA	
[2] 7		-720	-691	-522	-521	-525	-528	-558	-585	106.1 mA	
[3] 8		-732	-637	-507	-505	-513	-508	-537	-543	146.0 mA	500 ml NaHCO3
9		-783	-701	-510	-509	-513	-518	-570	-537	197.3 mA	
10		-706	-675	-510	-512	-513	-516	-550	-548	176.4 mA	
13		-693	-653	-506	-507	-508	-512	-538	-582	131.8 mA	
15		-711	-660	-513	-513	-515	-520	-542	-546	120.2 mA	
21		-587	-622	-507	-508	-506	-510	-523	-527	78.8 mA	
24		-641	-653	-497	-498	-501	-509	-599	-561	67.1 mA	
[4] 28	a.m.	-555	-641	-500	-501	-502	-504	-531	-524	64.1 mA	
[5] 28	p.m.	-706	-732	-565	-559	-571	-575	-663	-642	79.6 mA	
POTENTIAL SHIFTS:											
[2]-[1]		-288	-260	-94	-92	-97	-100	-124	-156	106.1 mA	
[3]-[1]		-300	-205	-79	-76	-85	-80	-103	-114	146.0 mA	
[3]-[2]		-12	+54	+15	+16	+12	+20	+21	+42	39.9 mA	
[4]-[1]		-123	-210	-72	-72	-74	-76	-97	-95	64.1 mA	
[5]-[4]		-151	-91	-65	-58	-69	-71	-132	-118	15.5 mA	

(5.3.4. cont'd)

This treatment produced immediate changes for the cathodic protection system. The application of the NaOH solution resulted in an immediate doubling of the current transfer to this "tank" from 54.1 mA to 108.1 mA d.c. A comparison of the corresponding average polarized "tank-to-soil" potentials is as follows:

Average "Tank-to-Soil" Potentials (mV wrt. Cu/CuSO4)

References	Before October 12th	After October 12th
A1 (Gravel bottom)	-776	-692
B1 (Sand-bottom)	-728	-689
A2/A3 (Gravel-top)	-506	-611
B2/B3 (Sand-top)	-550	-586

This data indicated that treatment with the NaOH solution significantly improved the polarization shift on the top surfaces of the tank, while some loss of polarization occurred at the bottom surfaces of the tank.

(5.3.4. cont'd)

The fact that there was some loss of polarization on the bottom surfaces of the tank, even though the total current output of the anodes (below the "tank") doubled, indicates that there was a major redistribution of cathodic protection current, with a much greater proportion of the current reaching the top aerated surfaces of the "tank."

A comparison of the "IR-drop" magnitude at the reference locations directly over the "tank" after treatment with the NaOH solution resulted in an interesting observation; this data (Appendix "C") is summarized in the following table.

"IR-Drop" Values (mV)

	October 12th			October 16th		
	ON	OFF	"IR"	ON	OFF	"IR"
A2 (Gravel)	568	512	56 mV	612	612	0
A2 (Gravel)	512	499	13 mV	610	610	0
B2 (Sand)	524	510	14 mV	597	596	1
B3 (Sand)	638	589	49 mV	577	576	1

After this specimen was treated with the NaOH solution, the "IR-Drop" component of the "tank-to-soil" potentials on top of the "tank" virtually disappeared! Furthermore, this observation remained consistent throughout the remainder of

(5.3.4. cont'd)

the experiment, until an anode was added over the tank (February 19, 1990); (Appendix "C")/

Comment

The chemical treatment only produced short term results. The effect on the polarized tank potentials peaked within one week (refer to Table 7 - February 17); all surfaces of the tank had shifted in the negative direction with respect to their values prior to the chemical application, due to the extremely high current density that was maintained for a five day period.

Shortly thereafter, the high current density receded and therefore surfaces of the tank depolarized. 250 ml of distilled water were distributed over the top of the tank on February 23rd, to reverse this trend. The total output to Specimen #3 increased from 63.0 mA to 88.1 mA, with little corresponding effect on "tank-to-soil" potentials. Within a few days, both the d.c. output and the polarized potentials of the "tanks" surface resumed their decline.

.5 The rectifier's output voltage was increased prior to recording data on October 27th, 1989. The voltage was maintained at approximately 10.1 V d.c. during the period from October 27th to November 28th, 1989. The current output to Specimen #3 varied from 64.1 mA d.c. to 197.3 mA d.c. (244.66 to 753.05 mA/sq.m., OR 22.78 to 70.11 mA/sq.ft. average) as various solutions were added to the soil. This data is summarized in Table 8 (pg. 74).

TABLE 8: SPECIMEN NO. 3,

[1 SEC "OFF" TANK POTENTIALS (@ Buried References; mV wrt CSE)]

	DATE	@	BELOW TANK A1	BELOW TANK B1	ABOVE TANK A2	ABOVE TANK A3	ABOVE TANK B2	ABOVE TANK B3	TANK SIDES ZL	TANK SIDES ZR	CURRENT (mA)	COMMENTS
[1]	Sep 19		-432	-431	-428	-429	-428	-428	-434	-429	0.0	Native
	Jan 25		-521	-483	-450	-450	-450	-452	-489	-470	34.3 mA @ 12 V d.c.	
	Feb 1		--	--	--	--	--	--	--	--	36.5 mA	
	5		-434	-382	-368	-367	-374	-373	-373	-373	32.1 mA	
	7	a.m.	-489	-476	-451	-448	-449	-449	-461	-461	30.5 mA	
	7	p.m.	-551	-470	-456	-456	-457	-457	-466	-458	32.2 mA	
[2]	8	a.m.	-538	-481	-471	-471	-471	-471	-477	-483	33.7 mA	
	8	p.m.	-550	-497	-483	-483	-483	-484	-486	-485	41.9 mA	1.5 l Ca(SiO3)
	9		-545	-504	-495	-496	-495	-495	-496	-496	43.1 mA	
	12		-514	-497	-472	-472	-471	-471	-479	-477	29.7 mA	
[3]	14		-533	-478	-458	-456	-457	-456	-455	-458	24.0 mA	
POTENTIAL SHIFTS:												
[2]-[1]			-106	-50	-43	-42	-43	-43	-43	-54	33.7 mA	
[3]-[1]			-101	-47	-30	-27	-29	-28	-21	-29	24.0 mA	
[3]-[2]			+5	+3	+13	+15	+14	+15	+22	+25	9.7 mA	

(5.3.5. cont'd)

The immediate effect of the change in output voltage was an increase in the current output from 55.7 mA to 97.1 mA d.c. The corresponding "tank-to-soil" potentials shifted negative as expected. However, the level of polarization remained non-uniform despite the addition of the sodium bentonite, and NaOH solution to the backfill, and the increase in the d.c. output of the rectifier (refer to October 27, 1989 a.m. - Appendix "C").

Subsequent to this set of data being recorded, 500 ml of distilled water were added directly over Specimen #3; the October 27 p.m. data shows that the immediate effect of this additional moisture is negligible. However, both the current output and the tank's potentials continued to decline over time.

The sand and stone screenings over Specimen #3 were again treated with chemical solutions prior to the set of readings on November 8th. 500 ml of NaHCO3 solution (w/50 mg. of solute) were evenly distributed over the specimen.

The addition of the NaHCO3 solution caused a significant increase in the current output to this "tank" model to 197.3 mA. A slight negative shift of the "tank-to-soil" potentials was observed, however, this was only a short term effect. Although the rectifier output voltage was maintained at approximately 10.1 V d.c. the current steadily declined to 64.1 mA by November 28th. Further treatment with 500 ml of NaOH solution (25 mg. of solute) did not have a significant impact on the cathodic protection system.

(5.3.5. cont'd)

Although the initial soil treatment with NaOH solution produced some positive effects on the cathodic protection of this specimen, they were only short-term in duration. The overall result of the various chemical treatments is unacceptable; the polarized potentials on the various surfaces of the tank were non-uniform and the overall shift in polarized potential (wrt. "native") was inadequate. Therefore, it was decided that a new experimental procedure should be adopted for Specimen #3.

.6 Specimen #3 was excavated and re-backfilled prior to resuming the next stage of the procedure dated December 21, 1989 (Appendix "G"), only the 3" saturated sand layer in which the anodes are buried below the tank, remained from the original test set-up.

Specimen #3 was rebackfilled on January 24th, with clean sand and stone screenings mixed with Portland Cement, and sodium bentonite. The exact mix proportions were as follows:

a)	Side A:	Gravel	6 parts	(by vol.)
		Portland Cement	3 parts	
		Sodium Bentonite	2 parts	
b)	Side B:	Sand	6 parts	(by vol.)
		Portland Cement	3 parts	
		Sodium Bentonite	2 parts	

.7 The rectifiers output voltage was increased to 12 V d.c., on January 25th, 1990 to compensate for the installed diode. The voltage was maintained at approximately 12 V d.c. during the period from January 25th to February 14th, 1990. The current output to Specimen #3 varied from 24.0 mA to 43.1 mA d.c. This data is summarized in Table 9 (pg. 78).

The "tank-to-soil" potentials for this specimen were periodically monitored after the change in backfill. With no further alterations to the chemistry of the backfill between January 25th and February 8th, the current output remained stable between 30.5 mA and 34.3 mA d.c.

Water was added to this specimen through the funnel port, during this period to maintain the level of the water table. Although a large volume of water was added, no water was observed draining from either of the drainage ports.

Meanwhile it was observed that a line of hydrating cement was advancing from the gravel end of the specimen (near the funnel port), across the specimen to the sand-backfilled end. It appeared as if the water was being drawn up from the water table by the capillary action of this specially prepared backfill. The full depth of the backfill had hydrated within one (1) week, without the addition of any moisture directly over the tank.

On February 8th, 1990 further chemical treatment of the soil backfill was conducted. 1.5L of Ca(SiO3) solution (w/75 mg.

(5.3.7. cont'd)

of solute) were evenly distributed over this specimen. This chemical application caused the current transfer to Specimen #3 to increase from 33.7 mA to 41.9 mA d.c., but by February 14th, this had declined to 24.0 mA.

The "tank-to-soil" potentials moved in concert with the magnitude of the current output; initially shifting more negative, but reversing later as the current declined. Please note that the potentials across the top and on the sides of the "tank" were uniform, but the bottom surfaces were slightly more polarized. Very little polarization from native potentials was observed, (Table 9, pg. ___).

.8 Specimen #3 was temporarily depolarized on February 17th and 18th when a graphite reference was inadvertantly bonded to the tank. Subsequent to this, a graphite anode was added over the top of this tank, and the rectifier's output was drastically reduced to 2.2 mA @ 2.8 V d.c. These changes resulted in the tank surfaces being uniformly poorly polarized (February 20th, 1990 a.m. - Appendix "C").

Immediately following this set of readings, the "tank" specimen was treated with 1 L. of saturated $Ca(OH)_2$ solution, evenly distributed over the centre line of the "tank" and 500 ml of saturated $Ca(SiO_3)$ solution. (February 20, 1990 p.m. - Appendix "C").

TABLE 9: SPECIMEN NO. 3,

[1 SEC "OFF" TANK POTENTIALS (@ Buried References; mV wrt CSE)]

DATE	@	BELOW TANK A1	BELOW TANK B1	ABOVE TANK A2	ABOVE TANK A3	ABOVE TANK B2	ABOVE TANK B3	TANK SIDES ZL	TANK SIDES ZR	CURRENT (mA)	COMMENTS
[1] Sep 19		-432	-431	-428	-429	-428	-428	-434	-429	0.0	Native
20		-873	-972	-468	-442	-434	-466	-691	-661	8.1 mA	@ 2.8 V d.c.
Oct 10		-1125	-773	-519	-505	-525	-597	-615	-464?	50.7 mA	@ 6.1 V d.c.
[2] 12		-776	-728	-512	-499	-510	-589	-581	-633	54.1 mA	
[3] 13		-692	-689	-612	-610	-596	-576	-633	-668	108.1 mA	10% NaOH
17		-996	-1072	-760	-760	-760	-762	-818	-807	106.7 mA	
[4] 23	a.m.	-808	-840	-649	-649	-649	-651	-668	-673	63.0 mA	
[5] 23	p.m.	-859	-808	-641	-641	-643	-643	-670	-657	88.1 mA	250 ml H20
24		-884	-839	-630	-632	-630	-633	-662	-671	82.7 mA	
26		-704	-750	-596	-597	-595	-598	-619	-615	55.7 mA	
POTENTIAL SHIFTS:											
[2]-[1]		-344	-297	-84	-70	-82	-161	-147	-204	54.1 mA	
[3]-[1]		-260	-258	-184	-181	-168	-148	-199	-239	108.1 mA	
[3]-[2]		+84	+39	-100	-111	-86	+13	-52	-35	54.0 mA	
[4]-[1]		-376	-409	-221	-220	-221	-223	-234	-244	63.0 mA	
[5]-[1]		-427	-377	-213	-212	-215	-215	-236	-228	88.1 mA	
[5]-[4]		-51	+32	+8	+8	+6	+8	-2	+16	25.1 mA	

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(5.3.8. cont'd)

This chemical application caused an increase in the current transfer to Specimen #3 from 2.2 mA @ 2.8 V d.c. to 20.2 mA to 2.7 V d.c. The polarized potentials of the tank's surface shifted negative by approximately 140 mV to about -600 mV (CSE). The polarized potentials were fairly uniform with the exception of the data recorded at reference locations A3 and B2. The top surfaces of the tank, at these locations were slightly more polarized than the remainder of the tank due to their proximity to the top anode.

N.B. The current transfer to Specimen #3 was 20.2 mA @ 2.7 V d.c. (w/top anode) and 0.4 mA @ 2.7 V d.c. (w/o top anode).

The average pH on the surface of the backfill was approximately 9.25 prior to the chemical treatment. The average pH increased to approximately 12 following treatment with the Ca(OH)2 and Ca(SiO3) solutions.

Within 24 hours the "tank-to-soil" potentials had shifted to about -760 mV (CSE), even though the rectifier output had been reduced to 12.2 mA @ 2.3 V d.c., with one additional anode installed over the "tank."

.9 The impressed current anodes and negative connections for this "tank" were subsequently transformed to the d.c. power source on a custom designed, computerized data acquisition

(5.3.9 cont'd)

system. The six graphite references and a portable CSE were connected to the computerized instrumentation package. Detailed depolarization curves for Specimen #3 were produced by this instrumentation, (Appendix "F").

.10 Specimen #3 was monitored with the computerized data acquisition system from March 5 to March 7, 1990. The resulting "depolarization curves" are shown in Appendix "F."

These "tank-to-soil" potentials wrt. the graphite references were converted to Cu/CuSO4 readings. The graphs were grouped according to reference location (as noted), and are arranged in chronological order. The rectified d.c. outputs to Specimen #3 were altered as follows:

March 5, 1990 a.m.	50 mA @ 5.5 V d.c.
March 5, 1990 p.m.	30 mA @ 3.9 V d.c.
March 6, 1990 a.m.	15.1 mA @ 2.8 V d.c.
March 6, 1990 p.m.	15.9 mA @ 2.8 V d.c.
March 7, 1990	15.1 mA @ 2.6 V d.c.

Some general observations of the graphs in Appendix "F" are as follows:

i) with the exception of some instrumentation interference ($\pm$ 6 mV), the graphs are very flat; i.e., very little depolarization was observed during the 11 second period of current interruption.

ii) as the rectifier output was reduced from 50 mA d.c. to 15.1 mA d.c. the polarized potentials uniformly declined as follows:

Bottom surfaces (gravel):	-975 mV to -810 mV (CSE)
Top surfaces (gravel):	-980 mV to -780 mV (CSE)
Top surfaces (sand):	-990 mV to -790 mV (CSE)

iii) the power source associated with the computerized data acquisition system was designed to operate at constant current output; i,e., as the electrical circuit was altered, the rectifier's output voltage was automatically altered to maintain the present current output.

The rectifier output on March 7th varied as follows, as the configuration of the impressed current ground bed was changed:

a) 15.1 mA @ 2.6 V d.c. (w/top anodes);
b) 15.1 mA @ 6.9 V d.c. (w/out top anodes - bottom anodes only).

The depolarization curves for all of the references clearly indicate the moment of current interruption, as the "IR-drop" component of the "tank-to-soil" potentials is removed; the significant "IR-drop" values recorded at reference locations A3 and B2 is an indication of their proximity to the top anodes.

5.4 Discussion of Results

Specimen #2, the "Control" specimen, represents a typical uncoated tank installed in an aerated sand, or gravel backfill partially (or completely) above the water table. Such tanks have typically been very difficult to cathodically protect at uniformly polarized potentials, (refer to Section 2.0 Background). This "tank" specimen was not subjected to any applications of chemical solutions; the level of the water table was maintained with the addition of tapwater through the funnel port and the occasional addition of distilled water directly over the buried tank (to represent moisture provided by rainfall).

The possible electrochemical reactions that were taking place due to the application of CP are as follows:

1. Cathodic Reduction of 02;

   $(02) + 2H2O + e' \longrightarrow 4(OH)'$

   where E (02/H2O/OH-) = (1.229 - 0.059 pH) V vs. (SHE) electrode.

2. Cathodic Decomposition of Water

   $2(H2O) + 2e' \longrightarrow H2\uparrow + 2(OH)'$

   OR

   $2H + 2e' \longrightarrow H2\uparrow$

   Where E(H2/H2O) = (-0.59 pH) V vs. (SHE) electrode.

(5.4 cont'd)

3. Anodic Decomposition of Water

$$2(H2O) \longrightarrow O2\uparrow + 2(H)^{+} + 2e'$$

OR

$$4(OH)^{-} \longrightarrow O2\uparrow + 2H2O + 4e'$$

The cathodic reactions (1) and (2) involving the reduction of O2 and hydrogen evolution occur on the surface of the cathodically protected tank dependent upon its voltage. Reaction (3) for decomposition of water and oxygen evolution occurs at the working anode of the cathodic protection system and the voltage is more than the electrical potential given by reaction (1) (the reverse) reaction.

The average pH of the bulk soil (backfill) at the surface varied from 6.75 to 8.50. At these pH values both cathodic reactions (1 and 2) are possible, except that reaction 2 occurs only at polarized potentials more negative than -714 mV (CSE).

With the non-uniform level of cathodic protection around Specimen #2 ("Control") as shown in Tables 4 to 6, Reaction #2 (Cathodic Decomposition of Water) could not be supported on the upper surfaces of the tank (-470 mV to -560 mV {CSE}). Therefore the sole controlling electrochemical reaction caused by the transfer of the cathodic protection current is Reaction #1 (Cathodic Reduction of O2).

(5.4 cont'd)

Over the course of the experiments, the driving voltage was increased from 6.1 V d.c. to approximately 12 V d.c. during the periods covered in Tables 4 to 6. The corresponding current output increased from about 60 mA to about 75 mA over this time span, but temporarily peaked @ 128.8 mA. Accordingly the resistivity of the soil was not constant, possibly increasing due to leaching of the conducting ionic species. Despite this current increase the topside of the tank undergoes negligible increase in polarized potentials. This strongly indicates that the cathodic protection current is largely confined to the bottomsides of the tank. This latter conclusion is supported by the much higher average polarized potentials on the bottom sides of the tank with increasing current.

It is to be noted that polarized tank-to-soil potentials for the "Control" exhibited fluctuations throughout the experiment and that both the polarized potentials and current generally increases temporarily upon addition of distilled water aliquots. The migration of the water, percolating through the soil introduces additional oxygen contents for the cathodic reduction reaction. Moreover, polarization voltages were obtained as high as -1000 to -1200 volts (CSE) on the "tank" bottom which would indicate cathodic evolution of H2 had also occurred.

The polarized potentials were carefully monitored using a computerized data acquisition system at cathodic protection currents ranging from 32.8 mA down to 15.0 mA. As illustrated by the depolarization curves (Appendix "E"), the

(5.4 cont'd)

large "IR-drop" upon discontinuing current at reference electrodes A1 and upon further supports the conclusion that the cathodic protection current is primarily confined to the tank bottom.

The technique of monitoring "tank-to-soil" potentials was alsc employed to determine if an addition of 1.5 L of tapwater (high in 02 and Ca(HCO3)2 content of about 4000 ppm would influence polarization properties over the top surfaces of the tank. Measurements on reference electrodes A3, B2, B3, and a portable CSE did show that a substantial increase in polarization potential to -760 to -860 mV did occur, (Appendix "E"). Accordingly, Ca(HCO3)2 probably underwent hydrolysis to Ca(OH)2, its precipitation at the upper tank surface leading to more effective polarization. However, close examination of these graphs comparing the rates of depolarization in comparison to the degree of polarization indicates a lack of uniformity in polarization over the total upper tank surface area.

Chemical solutions were added to each of the remaining two specimens, in an attempt to enhance the level of cathodic protection on the top surfaces of the "tanks." The results attributed to the addition of these chemicals, are compared to those obtained on Specimen #2.

As noted previously, Specimen #3 was initially treated with 500 ml of NaOH solution (w/50 mg of solute) that was used to wash 81 mg of sodium bentonite into the backfill. The

(5.4 cont'd)

treatment with these chemicals resulted in an immediate doubling of the current transfer to this "tank" to 108.1 mA d.c. The corresponding polarized "tank-to-soil" potentials became more uniform; i.e., the potentials on the top surfaces shifted in the cathodic direction, while those on the bottom surfaces shifted more anodic (Table 7).

The addition of the NaOH solution introduced the following reaction:

$$NaOH(aq) \longrightarrow (Na) + (OH)-$$

Therefore the resistivity of the backfill was reduced due to the presence of the ion conducting species from the caustic electrolyte thereby causing a substantial redistribution of the cathodic protection current, with a greater proportion reaching the top surfaces of the "tank". The decrease in the "IR-drop" values on the top of this tank (refer to pg. 72), despite the evidence of a substantial increase in current density at these surfaces, is attributed to a corresponding drastic reduction in the soil resistivity between this surface of the tank, and the buried graphite references.

Although the increase in the current density was observed immediately following the application of the NaOH solution, the polarized potentials did not peak until five days later. (Table 7). The higher cathodic protection current density that was maintained throughout this period, eventually

(5.4 cont'd)

polarized all of the surfaces of the tank, but the polarization was not uniform over the tank surface. During this period of elevated current density, the cathodic reduction of oxygen (Reaction 1) was proceeding at an accelerated rate thereby consuming free oxygen in the backfill. This environment continually depleted of O2 led to a greater degree of polarization.

The pH of the bulk solution (backfill) at the surface of this specimen varied from 6.75 to 8.50 (same as Specimen #2) prior to the application of NaOH solution. The introduction of hydroxyl ions to this backfill environment both by the external application of the NaOH, and by the accelerated cathodic reduction of oxygen had the following effects on pH and polarization:

1. the hydroxyl ion concentration was increased at the cathodically protected tank surface to a value considerably larger than the pH of the original soil as high as 8.50.

2. this effective hydroxyl ion concentration led to more effective cathodic protection over the entire tank surface.

During this period, the bottom surfaces of the tank reached polarized potentials more negative than -1000 mV (CSE). At these potentials, Cathodic Decomposition of Water (Reaction 2) can proceed in an environment with pH less than

(5.4 cont'd)

11.6. Although no attempt was made to measure pH at the bottom surfaces of the tank, it was believed to be less than 11.6; under these circumstances Reaction 2 was proceeding and hydrogen was being evolved.

Therefore it was observed that the addition of a small volume of NaOH solution increased the total cathodic protection current transferred to the tank specimen, and enhanced the overall polarization of the tank surface. However, the level of protection was still non-uniform; the bottom surfaces being more polarized to the point of possible hydrogen evolution.

Even so, these effects were only temporary in nature. The cathodic protection current declined over a ten day period to 63.0 mA with a corresponding reduction in polarized potentials (Table 7). This instability of polarization is attributed to the loss of caustic solution and a corresponding decrease in pH by drainage of the soil water especially in the region of the tank top. The addition of 250 ml of distilled water temporarily increased. The total current output with negligible effect on polarized potentials. The current output soon declined back to "normal." This "short-term" effect is again probably associated with the change of moisture content of the soil to more normal saturation determined by the environmental conditions.

(5.4 cont'd)

On October 26th, with the d.c. rectifier operating at an applied voltage of 6.1 V Specimen #3 and Specimen #2 ("Control") compared as follows:

	Specimen #3	Specimen #2 "Control"
Current transfer; (mA-d.c.)	55.7	64.1
Average Potential (bottom); (mV wrt. CSE)	-727	-648
Average Shift from Native (bottom); (mV)	-295	-237
Average Potential (top); (mV wrt. CSE)	-596	-490
Average Shift from Native (top); (mV)	-168	-78

This comparison clearly demonstrates that the addition of NaOH solution improved the level of polarization shift, both on the top and bottom surfaces of the tank; however, surface polarization is not uniform.

On October 27th, the applied voltage was increased to 10.1 V d.c., to produce an increase in current output from 55.7 to

(5.4 cont'd)

97.1 mA d.c. The net effect of this change in current output, on polarized potentials, was primarily restricted to the bottom surfaces of the tank. Despite the reduction in the resistivity of the backfill over the tank, this indicates that much of the protective current is confined to the bottomsides of the tank.

Specimen #3 was treated with an additional 500 ml of NaHCO3 solution (w/50 mg of solute). Again, this chemical application increased the total current output (Table 8): increase in current is to be expected from the increased ionic current due to the ionization reaction:

$$NaHCO3\ (aq) \longrightarrow Na^{+} + HCO3^{-}$$

In this case, the significant increase in current, produced by this chemical treatment had negligible effect on any of the "tank-to-soil" potentials because the pH of the soil solution was not altered to any substantial degree.

The backfill subjected to NaOH and NaHCO3 chemical treatments (Specimen #3) was replaced in order to investigate the influence of calcium containing electrolyte based on less solubility of the alkaline constituents. The constituents investigated were additions of Portland Cement mixed with sand/gravel, and sodium bentonite, Ca(SiO3) and Ca(SiO3) in combination with Ca(OH)2. This backfill containing Portland Cement in comparison to the regular sand-gravel mixture (Control Specimen #2) supported a lower and more constant electrical current; the polarization was

(5.4 cont'd)

more uniform but its degree over the bottom of the tank was decreased (Table 9). However, it was observed that the rate of depolarization over the top surfaces of the tank was practically negligible in this new soil backfill (see Appendix "C" for results from February 5th to 14th, 1990).

Addition of a Ca(SiO3) solution (5% by weight) to this new backfill led to insignificant influence on tank polarization (Table 9). Subsequent addition of a Ca(OH)2 - Ca(SiO3) slurry with the condition of reduced voltage and current (20.2 mA @ 2.7 V d.c.) resulted in more uniform polarization and shift to approximately -600 mV vs. (CSE). The measured pH at the soil surface was as high as 12 (the pH of saturated Ca(OH)2 solution is 12.5).

(5.4 cont'd)

On February 21st, with the d.c. rectifier operating at an applied voltage of 2.3 V, Specimen #3 and Specimen #2 ("Control") compared as follows:

	Specimen #3	Specimen #2 "Control"
Current transfer; (mA-d.c.)	12.2	4.6
Average Potential (bottom); (mV wrt. CSE)	-766	-709
Average Shift from Native (bottom); (mV)	-334	-298
Average Potential (top); (mV wrt. CSE)	-768	-671
Average Shift from Native (top); (mV)	-340	-259

This comparison demonstrates that the addition of a Ca(OH)2 - Ca(SiO3) slurry to a specially prepared, Portland Cement-based backfill, uniformly improves the level of cathodic protection on the overall tank surfaces.

It was possible to obtain extremely uniform and fully polarized "tank-to-soil" potentials of between -970 and -990 mV at all measured points around the tank surface at rectifier outputs of 50 mA applied at 5.5 volts. Moreover, the depolarized potentials determined over a period of

(5.4 cont;d)

~11 s. remained constant (Appendix "E"). One may conclude from these results, that application of a slightly soluble alkaline solution containing Ca(OH)2 - Ca(SiO3) has led to formation of a stable polarized film at the tank surface. This is probably associated with exceeding the solubility products of both alkaline additions:

$$Ca^{2+} + 2(OH)^- \longrightarrow Ca(OH)_2 \downarrow$$
$$Ca^{2+} + (SiO_3)^= \longrightarrow Ca(SiO_3) \downarrow$$

Photograph 6 and 7 depict Specimen #3 upon disassembling the experiment; please observe the clearly defined border between the two different backfills, and the white precipitate on the top tank surface.

As noted previously, Specimen #1 was initially treated with 500 ml of Ca(OH)2 slurry (w/50 mg of solute). This chemical treatment had a negligible effect upon the d.c. current transfer to the tank's surface; however the corresponding polarized "tank-to-soil" potentials became more uniform; i.e., the potentials on the top surface shifted slightly in the cathodic direction, while the bottom side shifted in the anodic direction (Table 1).

The addition of the Ca(OH)2 solution increases the pH of the soil water but the lack of a significant change in current output to this specimen, seems to indicate that the Ca(OH)2 solution had little effect on the soil resistivity of the backfill around the "tank." Nonetheless, the shift in the

Photograph #6 - Specimen #3 (w/Portand Cement-based backfill).

Photograph #7 - Specimen #3 (partially backfilled).

(5.4. cont'd)

polarized potentials clearly indicates a redistribution of the CP current, towards the top due to the increased alkalinity over this region of the tank surface. Moreover, the magnitude of the IR-drop decreased at each of the reference locations over the tank, but especially on the granular-backfilled side (A2/A3) as shown in Section 5.1.4. This clearly shows that the Ca(OH)2 content (increased pH) decreased the soil resistivity at these locations.

Although no attempt was made to measure pH at this stage of the experiment, the range of measured polarized potentials clearly indicates that Reaction (1), cathodic reduction of O2, was the sole reaction taking place at the tank surface. The combined effects of the depletion of oxygen, and the elevated pH at the tanks top surface permitted enhancement of polarized potentials.

As compared with the dramatic effects produced by the NaOH solution in Specimen #3, the modest effect of the addition of Ca(OH)2 solution was to improve the level of polarization on a longer term basis, without any risk of hydrogen evolution in this aerated environment.

(5.4 cont'd)

On October 26th, with the d.c. rectifier operating at an applied voltage of 6.1 V, Specimen #1 and Specimen #2 ("Control") compared as follows:

	Specimen #1	Specimen #2 "Control"
Current Transfer; (mA - d.c.)	62.7	64.1
Average Potential (bottom); (mV wrt. CSE)	-647	-648
Average Shift from Native (bottom); (mV)	-264	-237
Average Potential (top); (mV wrt. CSE)	-546	-490
Average Shift from Native (top); (mV)	-165	-78

This comparison clearly demonstrates that the addition of $Ca(OH)_2$ solution improved polarization levels and uniformity of protection of the top surface of the tank over a relatively short time frame; [Oct. 23rd to 26th].

On October 27th, the applied voltage was increased to 10.1 V d.c., to produce an increase in current output from 62.7 mA to 124.8 mA d.c. The net effect of this doubling in current output on polarized potentials, was relatively small over all regions of the tank surface but of largest magnitude on the tank bottom. Accordingly, the amounts of $Ca(OH)_2$ added

(5.4 cont'd)

to the soil had little long-term influence on redistributing the cathodic current over difference regions of the tank surface.

Subsequent additions of distilled water to maintain the moisture content of the backfill over the "tank" caused temporary increases in current output to Specimen #1. The corresponding "tank-to-soil" potentials over the tank generally exhibited a slight negative shift on the top surface, with a positive shift (depolarization) on the bottom surface as shown in Table 2. This was indicative of a minor redistribution in cathodic protection current, with a greater current density reaching the top surface, thereby depleting the oxygen at the soil/metal interface. Over a one month time span the "polarized" potentials were observed to remain relatively stable.

The increased current density produced a more significant cathodic shift in the polarized potentials on the bottom of the tank. This was especially true on the sand-backfilled end of the tank, where the polarized potentials were generally more negative then -850 mV (CSE). Possibly the increase in pH and the less effective migration of aerated water through the sand (relative to the granulated stone) led to current support by decomposition of water (Reaction 2) and hydrogen evolution at more negative potentials.

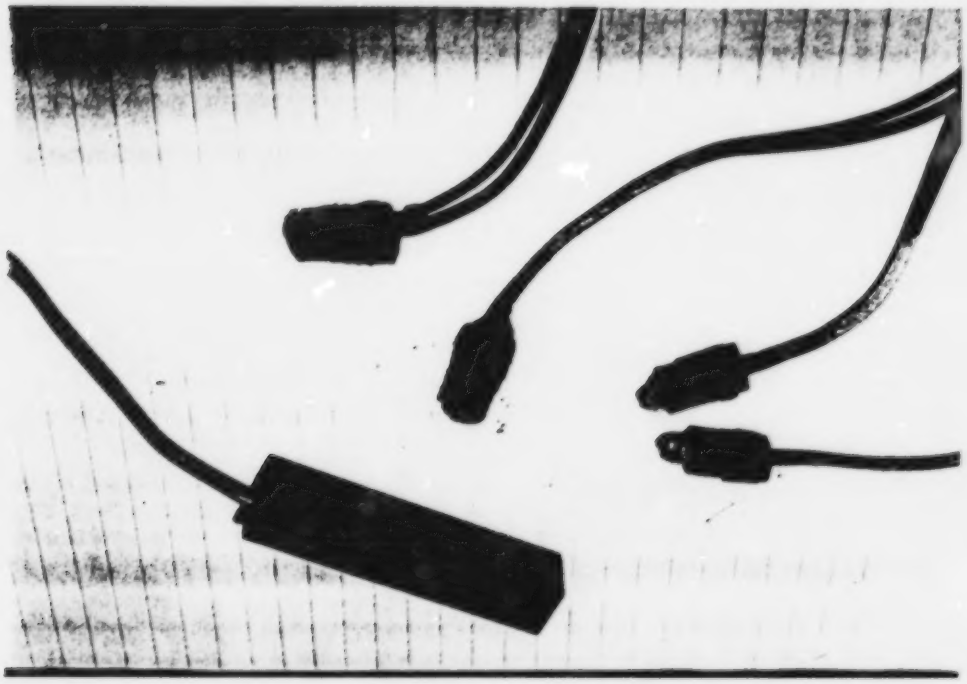
Specimen #1 was treated with 500 ml of NaHCO3 solution (w/25 mg of solute). The observed results, were very similar to

(5.4 cont'd)

those documented for Specimen #3; i.e., an appreciable increase in current output, with negligible effect on any the "tank-to-soil" potentials because the pH of the soil solution was not allowed to any substantial degree.

Cathodic protection of this tank specimen, continued during the "Interim" period from November 28th to January 25th, although further chemical treatment and monitoring was temporarily interrupted pending a revised experimental procedure. It was found that the four graphite anodes for this specimen were substantially consumed during this period. (Photographs 8 and 9). Despite the fact that the rectifier output was increased to 12 V d.c., the current transfer to Specimen #1 underwent a substantial decline leading to decrease of the "tank-to-soil" potentials (Table 3).

On February 7th, a small area of sand was excavated to allow a small plate, whose corroded surface had been treated with "tannin," to be backfilled and bonded into the CP system with Specimen #1. The introduction of this additional surface area caused a dramatic increase in current output; this was a short-term symptom that did not appear to affect the polarized potentials of the tank. The d.c. rectifiers current output declined to its former level when the surface of the "tannin" plate polarized to an equal potential as Specimen #1, (Appendix "A").



Photograph #8 - Consumed Graphite Anodes;
Specimen #1

Photograph #9: Excavated Anode Locations (N.B. Colloquial Graphite in sand backfill in corners).

(5.4 cont'd)

Specimen #1 was subsequently treated with 1 L of $Ca(NO2)2$ solution, followed by 500 ml of $Ca(OH)2$. As shown in Table 3, this treatment resulted in an extraordinary, short-term, increase in the output of the original four graphite anodes from 33.3 mA to 1180 mA d.c. (4504 mA/sq.m. OR 419 mA/sq.ft.). This large increase in the resistivity of the soil by the ionic species produced by the following reactions:

$$Ca(NO2)\ (aq) \longrightarrow Ca^{2+} + 2(NO2)-$$
$$Ca(OH)2\ (aq) \longrightarrow Ca^{2+} + 2(OH)-$$

Although the solubility of $Ca(OH)2$ is relatively small (1.85 g/L), the solubility of $Ca(NO2)2$ is large (45.9 g/L) leading to a marked increase in the conductivity of the soil water. A more umarkable property of $Ca(NO2)2$ is its action as an oxygen scavenger:

$$Ca(NO2)2 + O2(aq) \longrightarrow Ca(NO3)$$

Accordingly the combined effect of the $Ca(OH)2$ - $Ca(NO2)2$ chemical addition as a slurry was to lead to increased solution conductivity, scavenging or $O2$ and a subsequent remarkable increase in polarization properties.

By the time that the current output had stabilized at 4.5 mA the entire surface of the tank was uniformly polarized, with minimal depolarization observed during the period of current-interruption.

(5.4 cont'd)

After these results were observed, the soil was treated with the following chemical solutions:

i) 500 ml of $Ca(OH)_2$ slurry;
ii) 200 ml of $Ca(No_2)_2$ solution; followed by
iii) an additional 300 ml of $Ca(OH)_2$ slurry.

Two additional anodes were added over the top of Specimen #1 because of the decline in output of the four graphite anodes buried in the sand below the "tank." Further chemical treatments were also completed during this period (refer to Feb. 16 to 21; Appendix "A").

On February 21st, with the d.c. rectifier operating at an applied voltage of 2.3 V, Specimen #1 and Specimen #2 ("Control") compared as follows:

	Specimen #1	Specimen #2 "Control"
Current Transfer; (mA - d.c.)	44.9	4.6
Average Potential (bottom); (mV wrt. CSE)	-721	-709
Average Shift from Native (bottom); (mV)	-338	-298
Average Potential (top); (mV wrt. CSE)	-840	-671
Average Shift from Native (top); (mV)	-459	-259

(5.4 cont'd)

A comparison of this data, shows that the $Ca(NO_2)_2$ - $Ca(OH)_2$ chemical additions have resulted in an overall negative shift of the surface of Specimen #1. Moreover, the top surface was now more polarized than the bottom due to the proximity of the top anodes and the high current density at this surface.

This specimen was subsequently transferred to the power source associated with the computerized data acquisition system. The total current output was reduced from 50 mA to 15.1 mA d.c. to obtain a more uniform level of polarization. The depolarization curves can be found in Appendix "D." It is thus seen that the $Ca(NO_2)_2$ - $Ca(OH)_2$ solution treatment has led to the most uniformly complete polarization at an accepted level from -850 mV (CSE) to -740 mV, (CSE) at the lowest output level (March 2, 1990 p.m.).

Photographs 10 and 11 depict Specimen #1 during disassembly; please note the significant white $Ca(OH)_2$ precipitate only observed on the gravel backfilled end.

Photograph #10: Specimen #1,
(partially excavated)

Photograph #11: Specimen #1 w/$Ca(OH)_2$ Precipitate

6.0 CONCLUSIONS AND RECOMMENDATIONS

An examination of the results of this laboratory investigation into the improvement of uniformity and quality of cathodic protection of underground storage tanks backfilled in aerated soils, leads to the following conclusions:

.1 The addition of distilled water (moisture) directly over these tanks temporarily reduces soil resistivity near the surface. These alterations in resistivity generally caused an increase in cathodic protection current and a corresponding cathodic shift in polarized potentials. The temporary shift in polarized potentials was primarily confined to the bottom surface of the tank, and eventually declined, along with current output in this free-draining environment.

.2 Utilization of sodium-based chemicals (NaOH solution) produced temporary results only, as compared to the long term uniform cathodic polarization achieved through the use of calcium-based chemicals.

.3 The combined use of the following environmentally-compatible chemicals, Ca(OH)2 slurry, followed by Ca(SiO3) solution produced the following positive results at the soil metal interface of this "tank."

(6.3 cont'd)

a) high alkalinity environment;
b) low resistivity;
c) oxygen deficient environment;
d) limited oxygen diffusion through the backfill.

The combined effects of these chemical alterations allowed the "tank" to be uniformly polarized at reduced current densities, with virtually no depolarization observed in 11 s.

.4 The addition of Portland Cement to increase the alkalinity and to reduce the porosity of the granular backfill around newly installed tanks was a similarly beneficial means to uniformly polarize the surface of underground storage tanks.

.5 Homogeneity of the backfill is the essential condition to minimize the protective current of underground steel storage tanks; whether this condition is achieved during the tank's installation or subsequently prior to application of cathodic protection is not significant.

Phase II: a.c. EFFECTS ON d.c. POLARIZATION

7.0 SUMMARY /ABSTRACT

In recent times much attention has been directed at the influence of interfering dynamic a.c. on buried metallic pipelines. Much of the effort has dealt with ensuring the safety of personnel and equipment from the hazard of electrical shock and equipment failures due to the appearance of high energy a.c. surges on buried pipelines.

This experiment examines a less widely studied area of concern; the effect of a.c. on the performance of cathodic protection systems employed as pipelines to prevent corrosion.

Buried pipelines offer a low impedance path for transfer of a.c. earth currents and are therefore often under the influence of interfering a.c. earth currents. This investigation was performed on a laboratory model that simulated a long buried pipeline. Sixteen (16) events of switching from d.c./a.c. combination to d.c. and fourteen (14) events from d.c. only to the d.c./a.c. combination indicate 81% probability of increased cathodic polarization and 79% probability of reduced cathodic polarization respectively.

These tests indicate that the sacrificial anode method for cathodic protection systems is prone to the adverse effect of a.c. because they may not have the resource capacity to

(7.0 cont'd)

overcome the loss of cathodic polarization caused by a.c. interference. The impressed current method with adequate capacity can more easily be adjusted to counteract the loss of cathodic polarization caused by a.c. interference.

The adverse effect of interfering a.c. to pipeline cathodic protection in systems should not be overlooked by pipeline designers and operators of underground tank/piping facilities.

8.0 BACKGROUND: a.c. EFFECTS ON d.c. POLARIZATION

8.1 The Significant of the a.c. Interference Problems for Underground Bare Steel Tanks

8.1.1. Depolarization of unprotected steel surfaces by a.c. is known to have greatly accelerated the rate of of corrosion attack; a.c. is also known to result in the protective current requirement for cathodic protection being significantly increased. These adverse positive potential-shift effects have been reconfirmed for various metals commonly used including steel, lead, aluminum, zinc, and magnesium - except for copper, its surface potential being shifted rather uniquely in the cathodic direction by a.c. Even so, extremely little information has been published on the significance of a.c. to accelerate the corrosion of steel.

8.1.2. Since 1947, when cathodic protection was first utilized in Canada to protect underground pipelines, the utilization of a.c. power has increased about tenfold per consumer; since then a.c. power has also been widely distributed as the population density has also grown throughout the country to be utilized by nearly all potential owners and end-users of underground steel storage tanks. The cross-section of the electrical grounding neutral conductors to carry a.c. faults, unbalanced a.c. and to maintain an equalized earth potential has not, however, increased proportionately with this widespread utilization of electricity. As a result, there has been a vast increase in the density of a.c. conducted through the earth, and predominantly within the more conductive surface layer of soil.

(8.1.2. cont'd)

8.1.3. It has been determined that a.c. interference is very significant at the surfaces of underground pipelines, especially at ends, at points of crossing foreign underground metallic structures, and in proximity to overhead a.c. power lines, including the municipal power distribution lines as a result, the polarized pipe-to-soil potentials measured at these locations are significantly lower, and they are rapidly depolarized.

8.1.4. Similarities of d.c. interference to underground tanks and pipelines from a corrosion standpoint, and with regard to a.c. interference at the soil/metal interface surfaces are assumed to be equivalent. Therefore, any a.c. interferences should be primarily between tanks and piping at metallic discontinuities, near other electrical isolation, and concentrated at the end corners of buried tanks; also a.c. current density would be higher at vents and other risers of underground tank systems which are close to foreign metallic structures and utilities.

8.1.5. It is also expected, however, that the density of a.c. interference would be greatest at imperfections or "holidays" of well coated tanks, as compared to poorly coated or bare tanks and piping. Also the detrimental effects should be greatest in porous aerated soils. Therefore, this portion of the research and development is directed at assessing the rate of depolarization and the increase in protective current requirement for well

(8.1.5 cont'd)

coated tanks and piping in sand or soil backfills, i.e., primarily those which were installed from about 1980 to date. It is noted that applied protective current densities in the order of 3,000 mA/sq.ft. have been measured on pipelines; it is surmised due to no polarization that the a.c. current densities could be far greater where a.c. is found to be at pipe-to-soil potentials of up to 15 volts r.m.s.

8.1.6. It was determined that an evaluation could be more readily simulated for well coated piping by using small diameter 1" O.D. thin wall piping, and by inserting both high resistivity soil and shunts in the circuits to study the effects of high a.c. current densities at holidays.

8.1.7 It was surmised that interferences by a.c. would result in the reduced alkalinity of the protective film, and its more rapid depolarization on interrupting the protective current. It was anticipated that a.c. depolarization would be most significant for tanks and piping that are protected by impressed current, a.c. ripple in the d.c. output of rectifiers being expected to adversely effect the polarized surface potential. Therefore, this portion of this research and development program is primarily directed at the effectiveness of impressed current cathodic protection of underground tanks and piping (it is noted that this

(8.1.7 cont'd)

is the only type of cathodic protection system for which the "IR" polarized structure-to-soil potential values are proposed to be monitored by oil product marketing companies using remore monitoring units [RMU]).

8.1.8 The depolarization characteristics at holidays at the surfaces of aerated risers (where cathodic protection is minimal, and depolarization most rapid), and at the depth of tanks (where a.c. current exchange to earth could be expected to be greatest, due to the higher conductivity of this soil environment) are also examined.

8.1.9 The fact that steel is a million times better conductor than any natural electrolyte, and that a.c. pipe-to-soil potentials in the range of 30 to 100 volts r.m.s. or more have been measured on many pipelines, would indicate that stray a.c. potentials of several volts may be expected in underground storage tank systems. The fact that significant a.c. on buried tank-piping systems may be because the potentials do not exceed the caution level of 15 volts r.m.s. or the perception level, and because digital survey voltmeters now used reject a.c.

9.0 LABORATORY APPARATUS

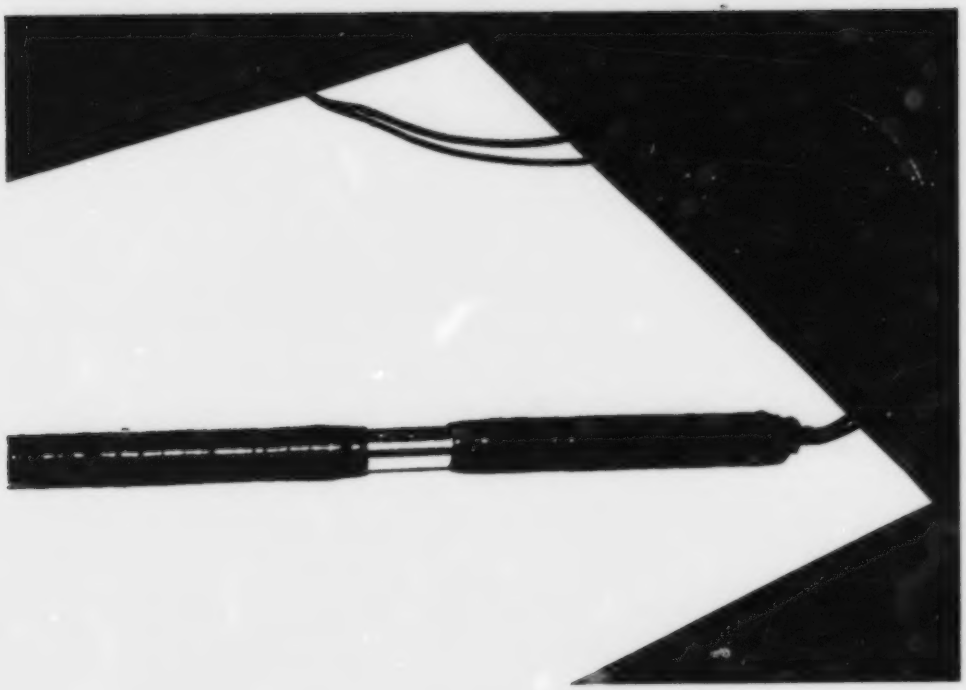
9.1 Laboratory Model - a.c Effects on Depolarization

The model components and connections are as shown in Figure 3. The layout for a series of tests was arranged in a "sand-box" to simulate a long underground pipeline. Two 305 mm long sections of 13 mm (1/3 in.) steel pipes were buried. Each pipe was completely insulated with the exception of a 25.4 mm (1 in.) long bare portion to provide a "holiday" of 10.12 cm2 (1.57 cm, 1 in2). Four (4) insulated lead wires were attached to each pipe to provide electrical access for anodes, a.c. input, joining the pipe sections and monitoring purposes. The sand adjacent to the pipes was kept moist with tap water added from time to time. The sand between the widely separated structures was purposely dry to provide a separation characterized by high resistivity. Two (2) copper electrodes with insulated lead wires were buried about 26 mm (1 in.) laterally from the holiday and connected to the a.c. supply to provide the variable stray a.c. earth current as and when required.

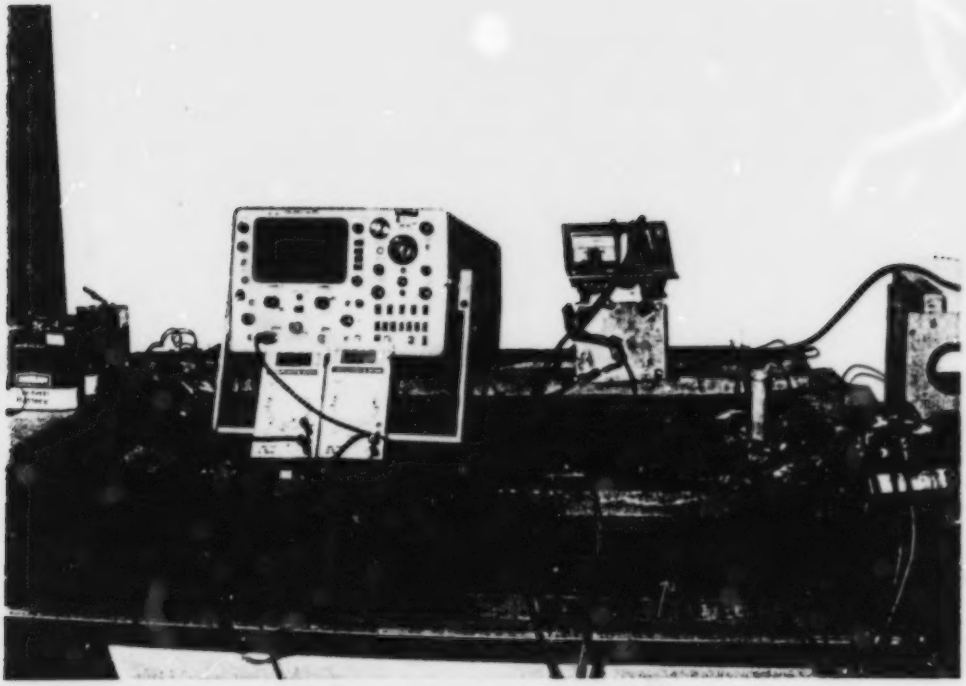
9.2 Anodes and Reference Cells

Two (2) 3 lb. magnesium anodes, one for each pipe, were buried near the structures but not in the immediate area of the holiday. These anodes were used to provide cathodic polarizing current by (2) the sacrificial anodes mode and (b) the impressed current mode, as required.

The reference cells were Cu/CuSO4 located on the surface between the pipe holiday and the a.c. electrode.



Photograph #12: Laboratory Model - (Phase II).



Photograph #13: Laboratory Set-Up - Phase II.

10.0 LABORATORY PROCEDURE

The investigation was carried out in two (2) parts with respect to the manner of supplying d.c. to the structures to be protected.

Part (A) used the sacrificial anode mode with 3 lb. magnesium anodes. The stray a.c. was supplied by a variable voltage source connected to the a.c. electrodes located near the structure.

Voltage and current readings were recorded for a variety of conditions. Specifically, the attached Summary of Data (Appendix "L") includes the report of 15 events ranging in duration of tens of minutes to periods of more than 24 hours. These situations consisted of a number of events consisting of (a) a.c. combination switched to d.c. only and (b) d.c. only switched to the a.c.-d.c. combination. Individual instruments were used to measure the values of interest, they were read visually and recorded manually.

Events 13, 14, and 15 are manually read from the impressed current method portion of the investigation and show a wider variance of change due to the ability to alter current inputs.

(10.0 cont'd)

Part (B) used the impressed current mode of supplying d.c. current to the structures to be protected. The anodes described in Part (A) were disconnected from each structure and connected directly to the d.c. source available from the computerized data acquisition equipment. The separated structures were electrically joined by an insulated lead wire containing single pole switch, S, (Figure 3). The d.c. had a manually operated voltage control mechanism but was also equipped with sensing to provide a constant d.c. current supply.

The analog to digital terminals of the data acquisition system were connected to the structure and reference cell. Output voltage to the system was measured by a digital voltmeter along with digital ammeters to measure a.c. and d.c. current values.

The variable a.c. source was connected, as required, in the same manner as in Part (A).

The computerized data acquisition equipment sampled, values of d.c. potential and a.c. potential at 110 ms intervals over a period of 11 sec. while the d.c. supply was OFF and d.c. depolarization was taking place. The limitation of this equipment were as follows:

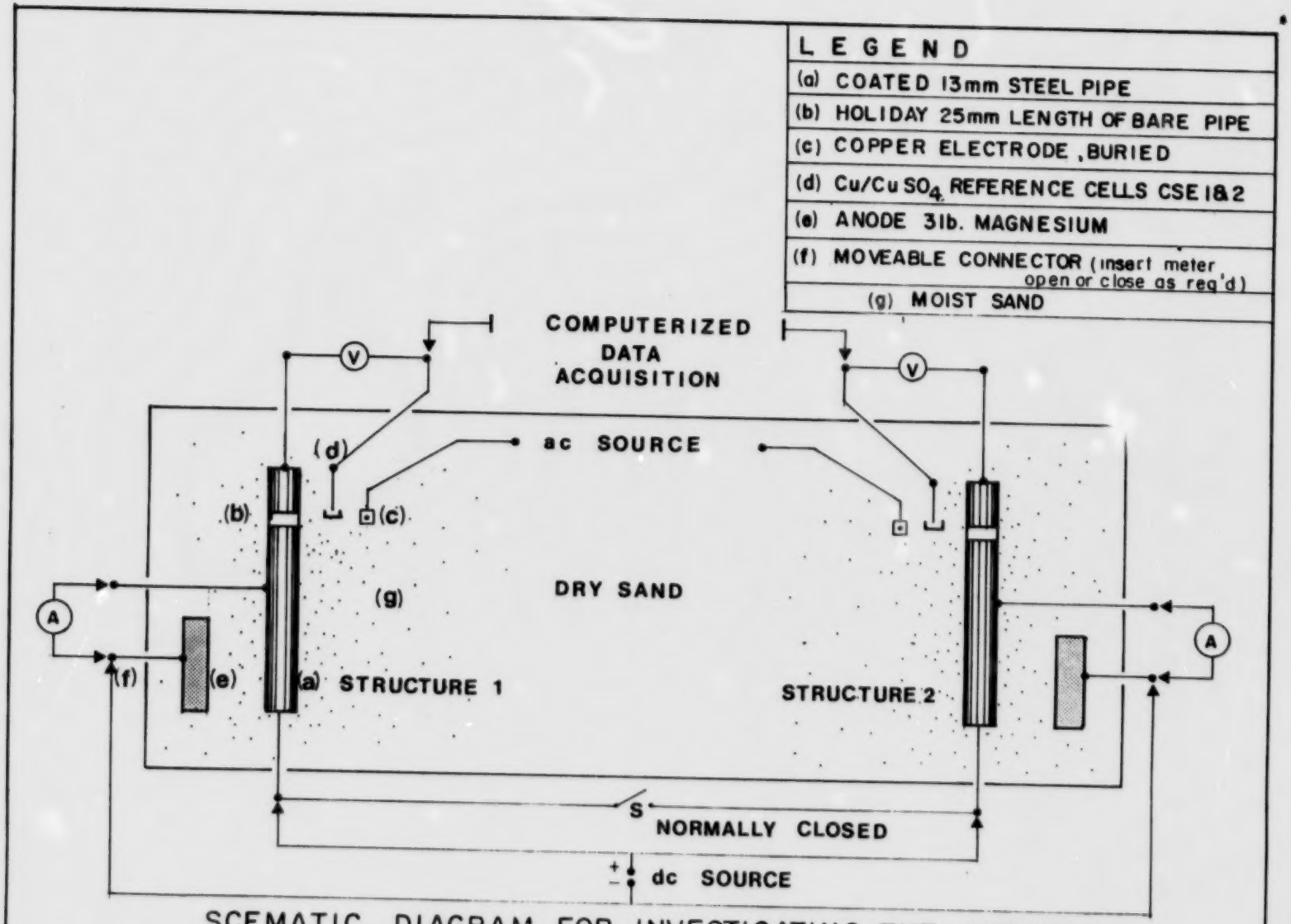
(a) the maximum structure to reference cell potential

(10.0 cont'd)

that could be accomodated was 1.542 V d.c. and,

(b) the inability to meaningfully display potentials when a.c. is superimposed on the d.c. cathodic protection current.

The latter deficiency was partially overcome by superimposing the a.c. signal for a portion of the 11 sec. OFF period only.



SCEMATIC DIAGRAM FOR INVESTIGATING THE INFLUENCE OF STRAY a.c. ON CATHODICALLY PROTECTED BURIED STRUCTURES

FIGURE 3

11.0 RESULTS

11.1 Part (A)

Some data typical of the "a.c./d.c. to d.c." and d.c. to a.c./d.c. events pertaining to the sacrificial anode method are given in Appendix "H."

Appendix "I" tabulates the total events observed during this investigation as they pertain to the series of a.c./d.c. to d.c. and d.c. to a.c./d.c. inputs to the structures.

Appendix "J" tabulates the probability distribution of the results reported in Appendix "I."

Appendix "K" tabulates observations of single events made at the start of employing the impressed current method and pertaining to structure to soil potentials for;

(a) a.c./d.c. to nil input,

(b) Nil ("native" soil potential) to a.c. input a.c. to a.c./d.c. input.

(c) a.c. to a.c./d.c. input

Item (b) was not examined but the observation suggests the need for more study.

(11.2 cont'd)

11.2 Part (B)

The computerized data acquisition system was used to discern the influence of a.c. superimposed on a structure receiving d.c. by the impressed current method.

Figures 4 and 5 are the depolarization curves for the application of d.c. only to Structure 1 (CSE1) and Structure 2 (CSE2). The figures are marked to show the value of voltage and current involved prior to d.c. current OFF.

Figures 4 and 5 are a remarkable picture of the structures depolarizing over a 11.66 sec. period.

These figures indicate that the structure(s) is not well polarized since the instant-off voltage to reference cell is about -0.78 mV and about -0.62 V at 1 sec. elapsed time. Good practice would expect -0.850 V at about 1 sec. elapsed time.

Figures 6 and 7 depict the condition form a.c./d.c.-ON to d.c.-OFF for 11 seconds. Figure 7 is marked up free hand in an attempt to trace an approximately average d.c. potential during the 11 sec. with d.c. OFF. Figure 6 and 7 are typical for all d.c. depolarization events where a.c. continued being applied to the

(11.2 cont'd)

structure for the full 11 sec. The data sampling speed is not synchronized with the 60 Hz a.c. source and is therefore of little value in deciphering the effect a.c. has on the cathodic depolarization of the structure under study.

Figures 8 and 9 show for Structures 1 and 2, respectively, the measured a.c. voltage to reference cell with a.c. only applied. This further illustrates that data acquisition while the a.c. is applied during the complete 11 sec. period is not helpful in determining the exact influence of a.c. on the depolarizing event.

To overcome this deficiency several conditions of combined a.c./d.c. were graphed as follows. Data acquisition was commenced with d.c. only for about 1 sec. duration, then a.c. was superimposed for a period of 2 to 3 sec. and the depolarizing d.c. only was continued for the remainder of the 11 sec. period. Under the same conditions of d.c. only a depolarizing curve was produced. A comparison of the two graphs, in particular the points where a.c. started and finished were of interest. Visual examination by overlaying the graphs showed a remarkable similarity between identical points on the graphs. Figures 20 and 23 and figures 12 and 13 were produced by the above procedure.

(11.2 cont'd)

Cathodic depolarization for Structures 1 and 2 are shown on Figure 20 and 21 for the described d.c. input. Figure 22 and 23 show the results of superimposing a.c. on the companion d.c. depolarization curve of Figure 20 and 21. Overlaying of these figures shows a visually noticeable cathodic depolarization due to the superimposing bust of a.c. to the d.c. depolarization procedure.

Cathodic depolarization for Structures 1 and 2 are shown on Figures 24 and 25 for the described d.c. input. Figure 26 and 27 show the results of superimposing a.c. on the companion d.c. depolarization current of Figure 24. Overlaying of these figures show no visually noticeable cathodic depolarization done to the superimposed bust of a.c. to the d.c. depolarization procedure.

12.0 CONCLUSIONS AND RECOMMENDATIONS

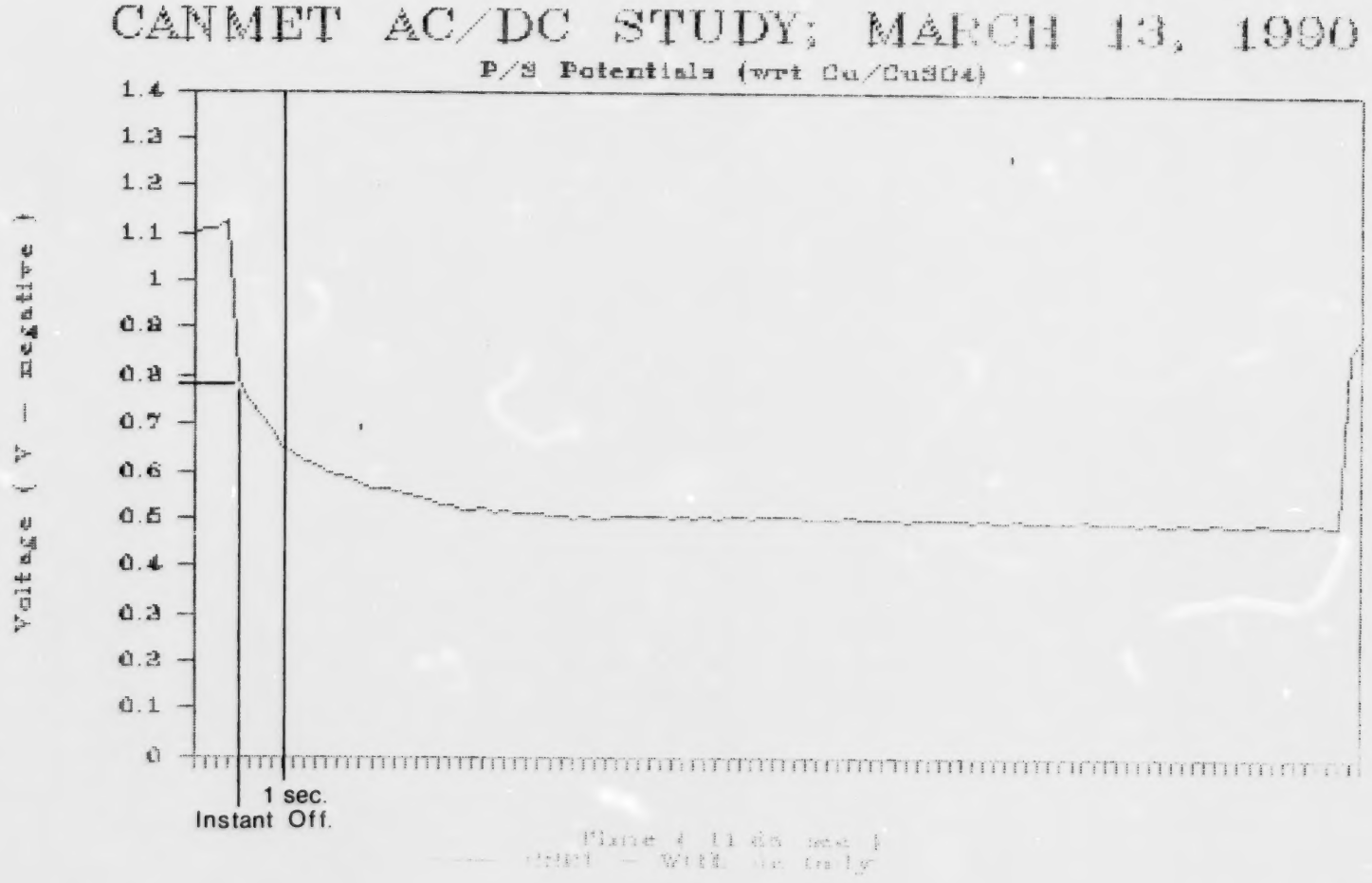
This investigation of the effects of a.c. on cathodically protected structures revealed that the effect could be adverse. In the situation where the stray a.c. current was superimposed on a structure under cathodic protection (from d.c. only to the a.c./d.c. combination) the structure-to-soil potential became more positive. A positive shift of 4.5% was the maximum observed in the laboratory tests.

On the other hand, when a structure under the combined influence of a.c./d.c. had the stray a.c. component removed (from a.c./d.c. to d.c. only) the structure-to-soil potential generally became more negative. A negative shift of 4.5% was the maximum observed in these laboratory tests.

The result of this investigation warrants designers and operators of cathodic protection systems to be aware of the effects of stray a.c. earth currents and consider corrective measures, as required by negotiations with offending parties or by design through automatic adjusting rectifiers of adequate capacity.

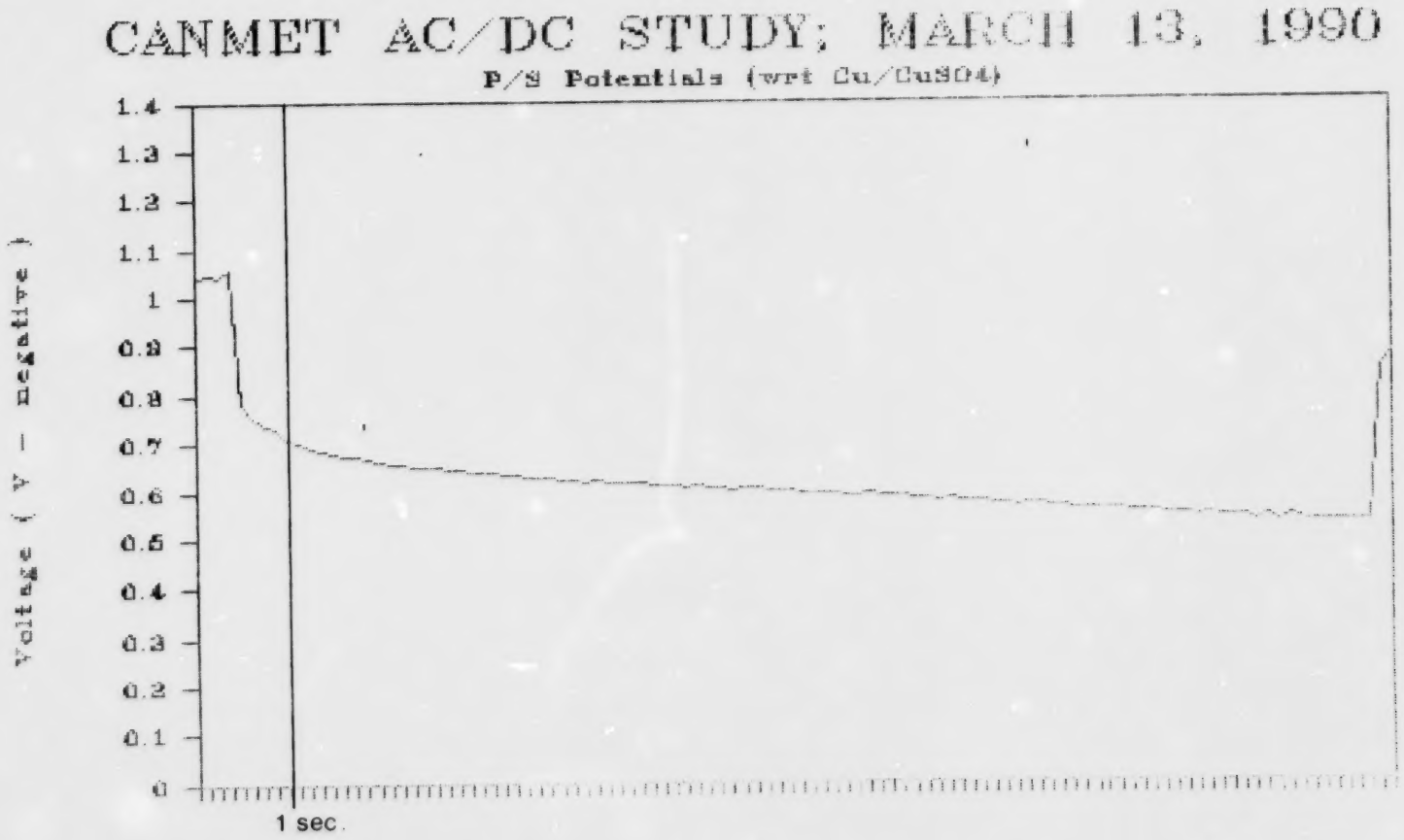
Meter Reading Prior to dc Off: Applied Voltage = 120 mV dc; Current = 1.47 mA dc

Figure 4



Meter Reading Prior to dc Off: Applied Voltage = 120 mV dc; Current = 1.52 mA dc

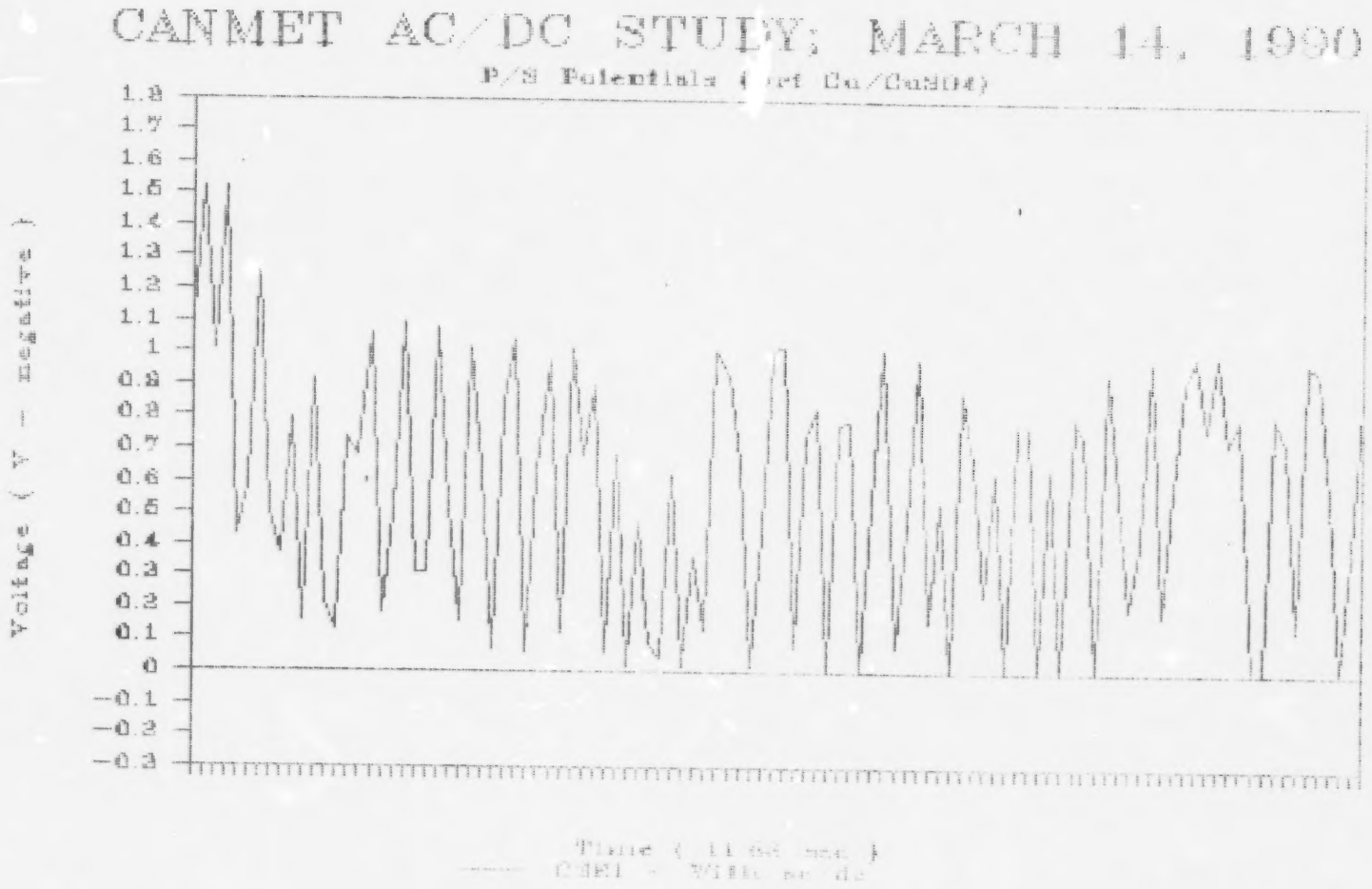
Figure 5



Meter Readings Prior to dc Off: Structure to Soil - dc = -1.146 V; ac = 0.378 V r.m.s.

Current to Structure - dc = 1.47 mA; ac = 2.15 mA r.m.s.

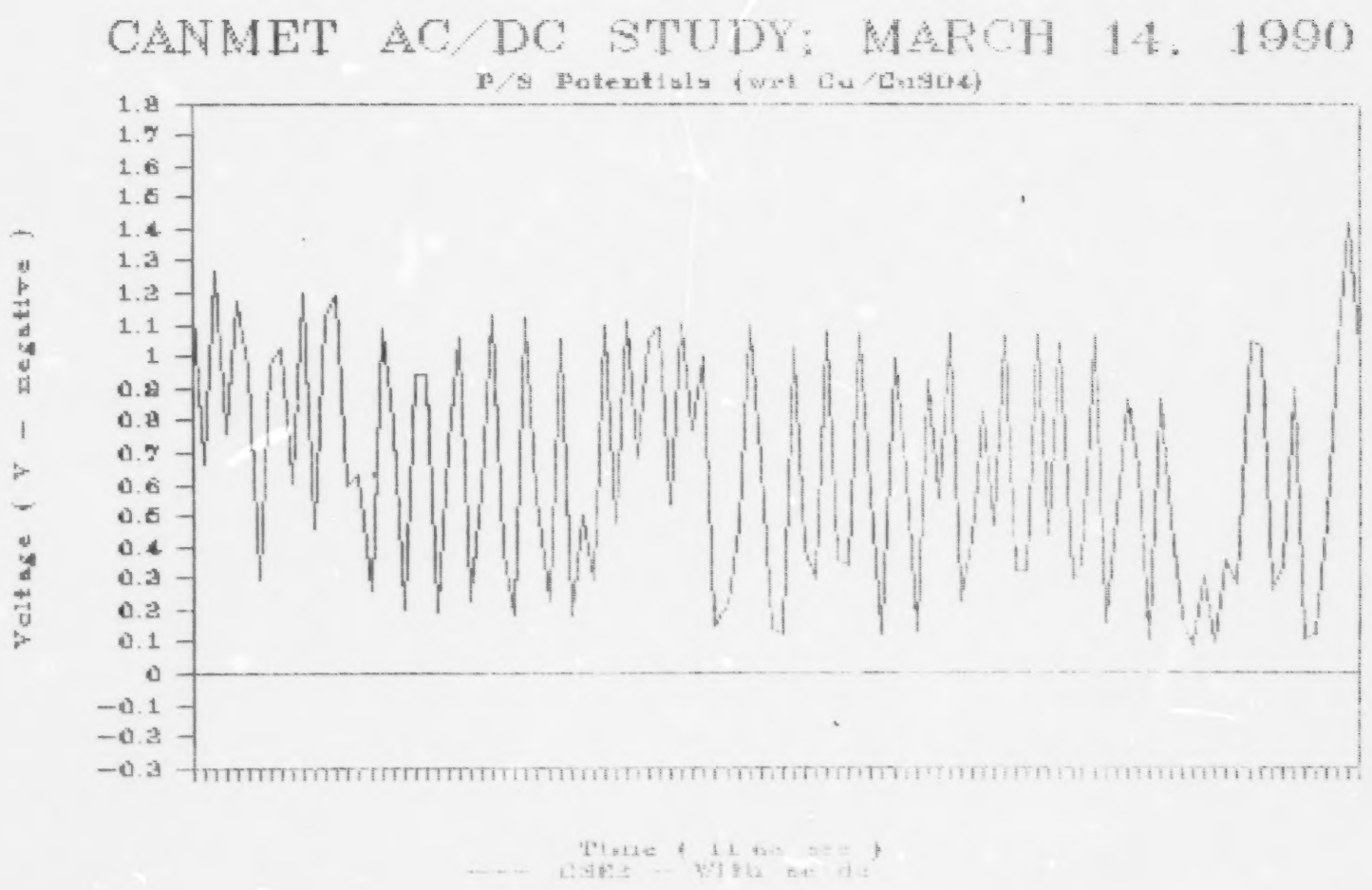
Figure 6



Meter Readings Prior to dc Off: Structure to Soil - dc = -1.113 V; ac = 0.365 V r.m.s.

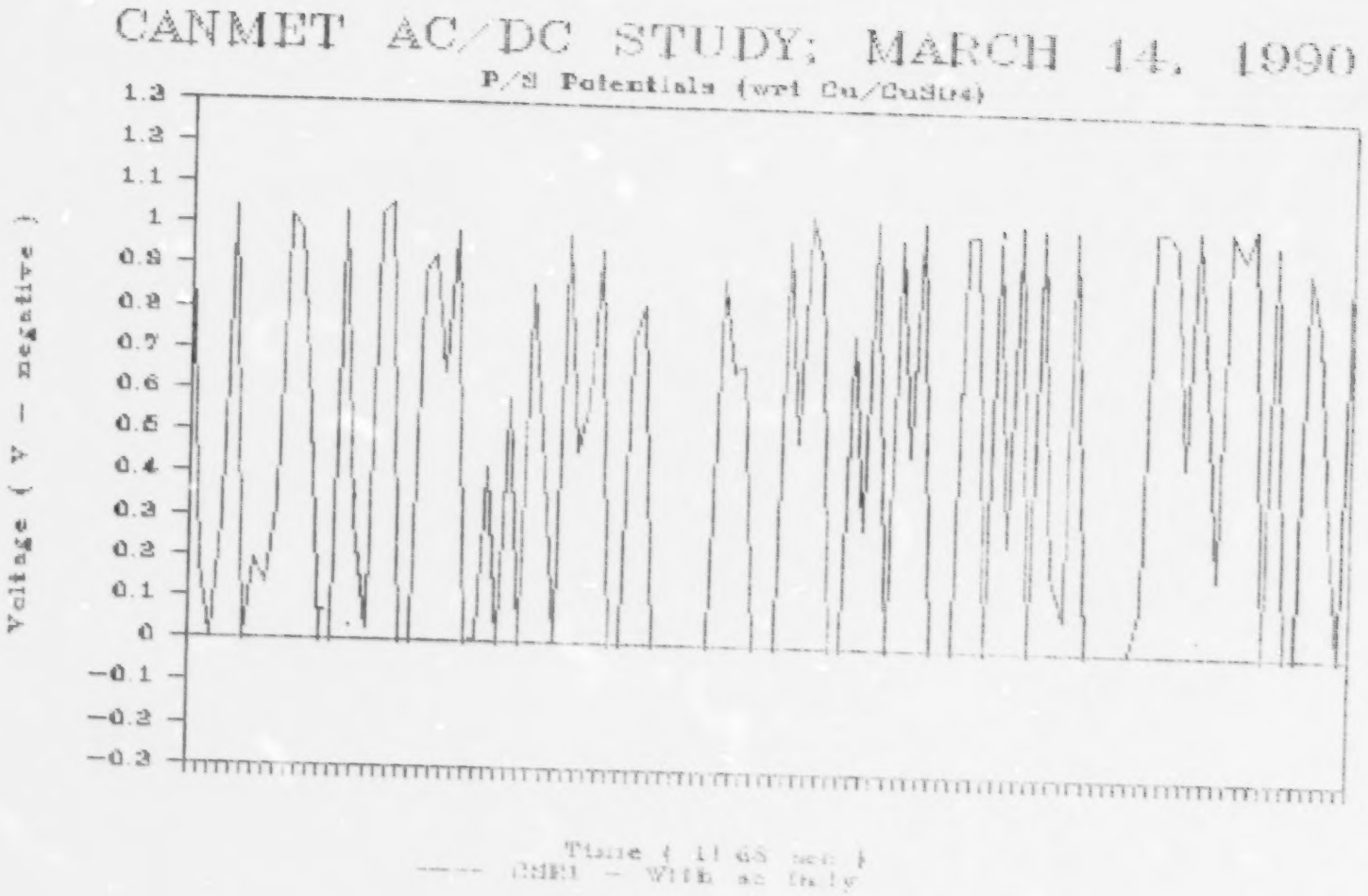
Current to Structure - dc = 1.58 mA; ac = 2.15 mA r.m.s.

Figure 7



A.C. Source - 2.0 V ac r.m.s. & 2.15 mA ac r.m.s.

Figure 8



A.C. Source - 2.0 V ac r.m.s. & 2.15 mA ac r.m.s.

Figure 9

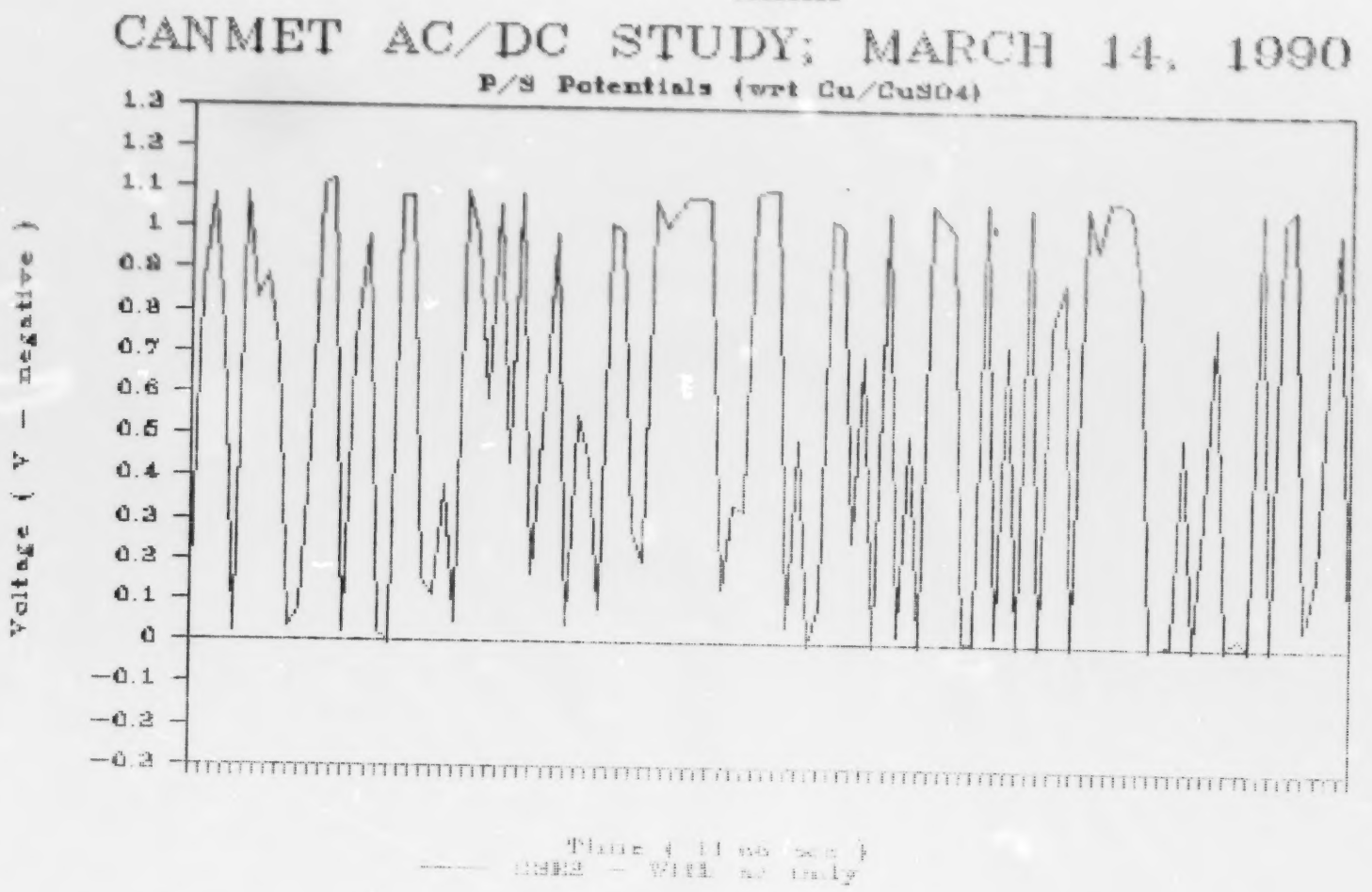


Figure 10

Identified on Summary of Data (Appendix L)

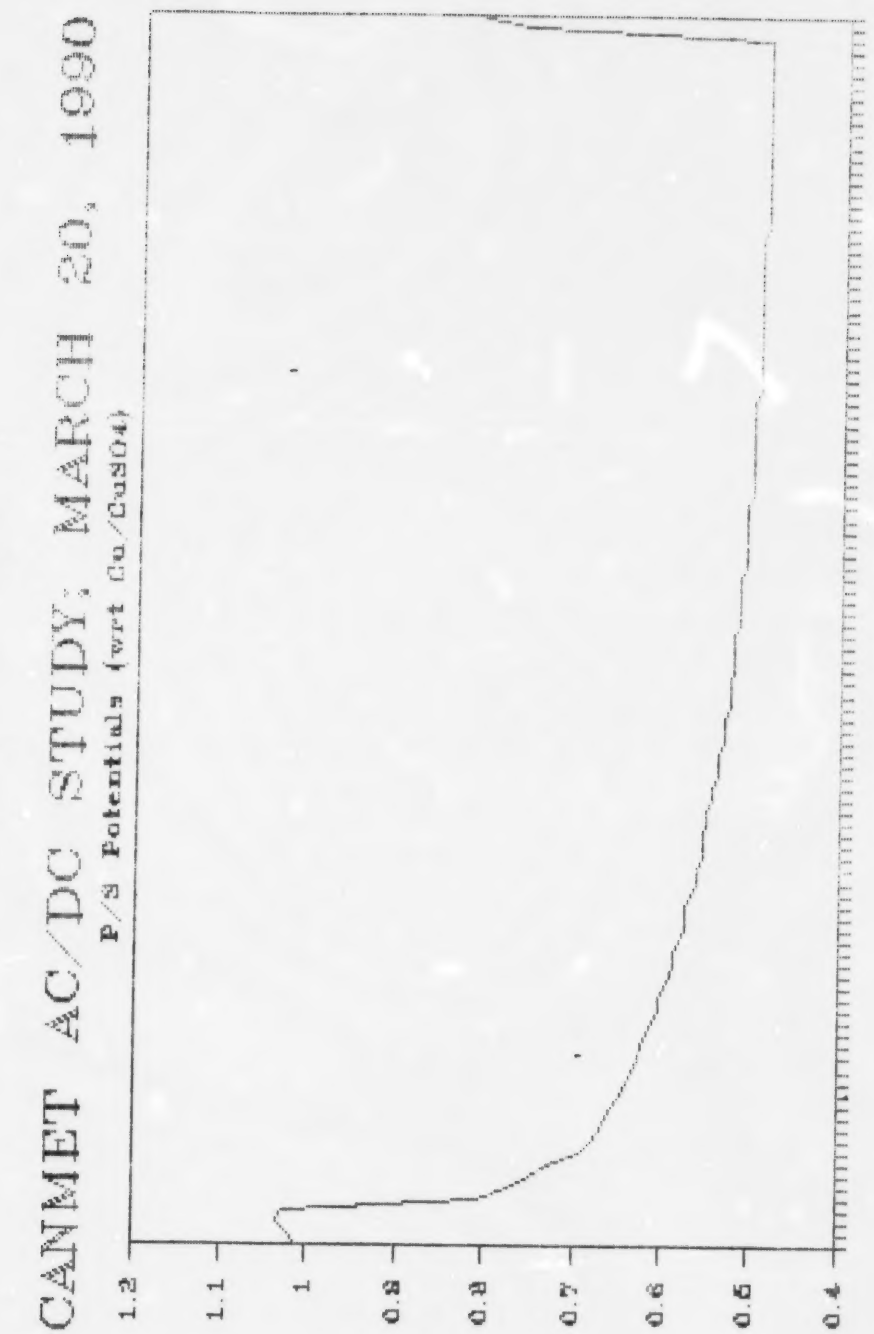


Figure 11

Identified on Summary of Data (Appendix L)

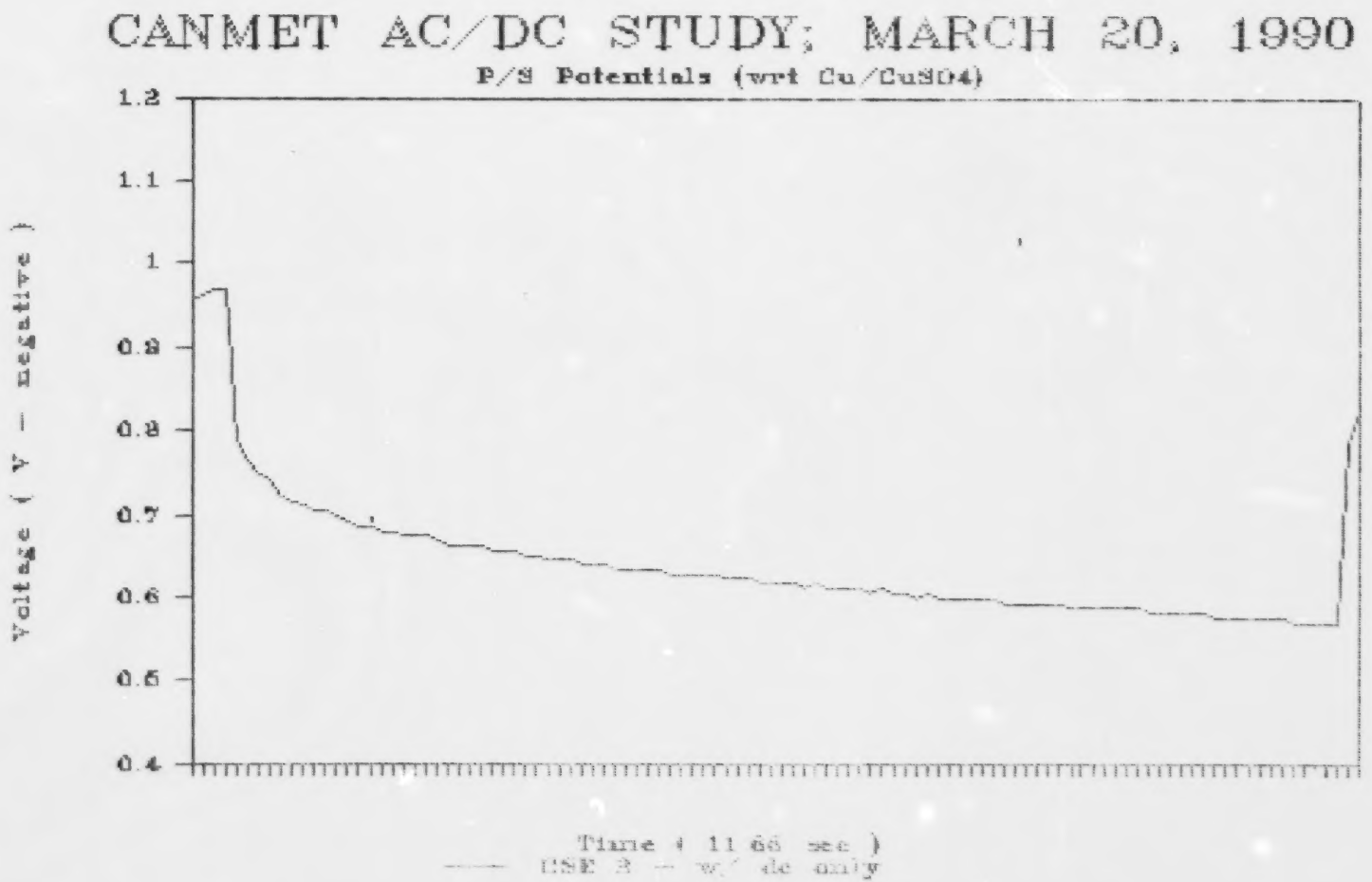


Figure 12

Identified on Summary of Data (Appendix L)

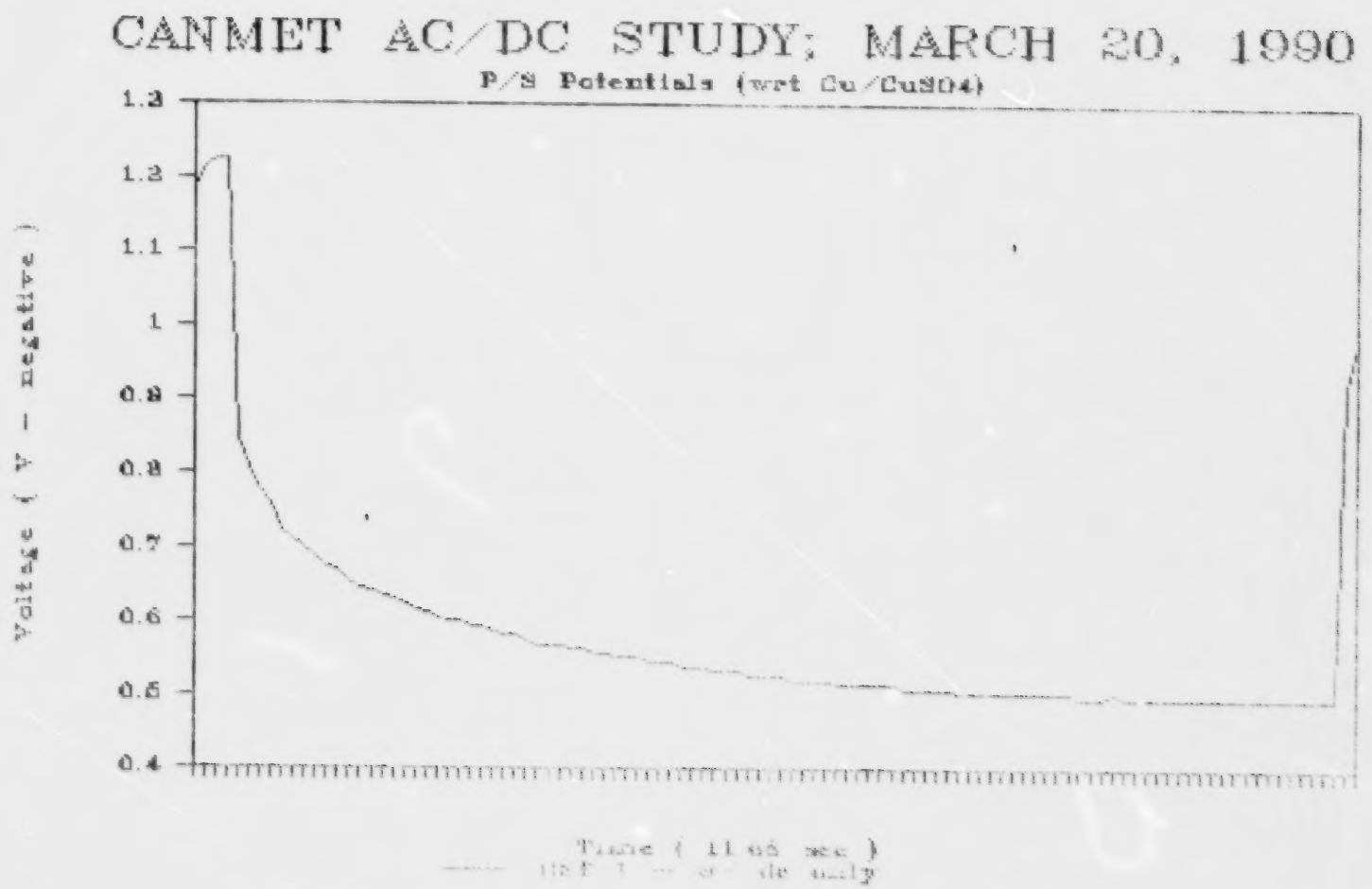


Figure 13

Identified on Summary of Data (Appendix L)

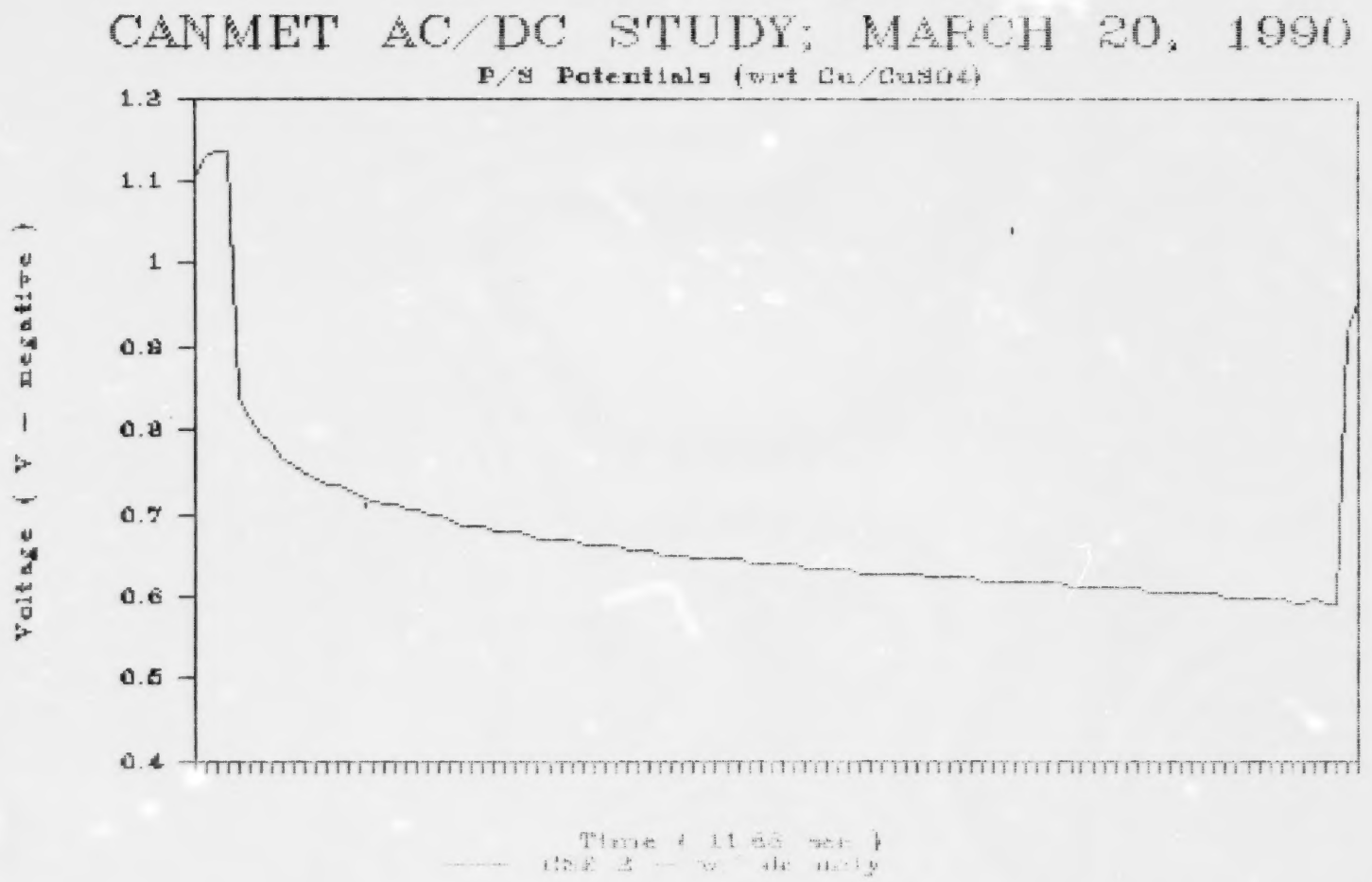


Figure 14

Identified on Summary of Data (Appendix L)

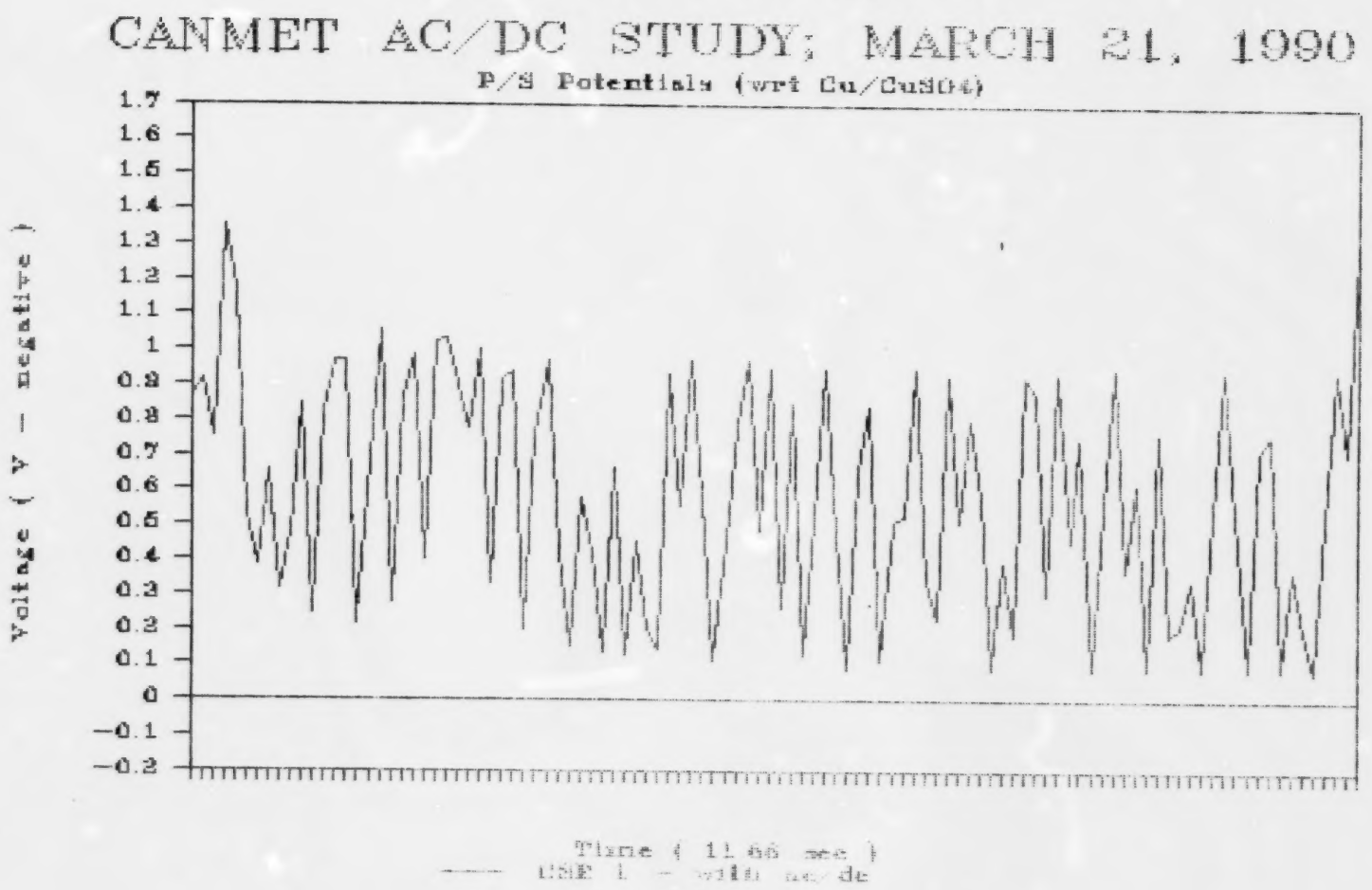


Figure 15

Identified on Summary of Data (Appendix L)

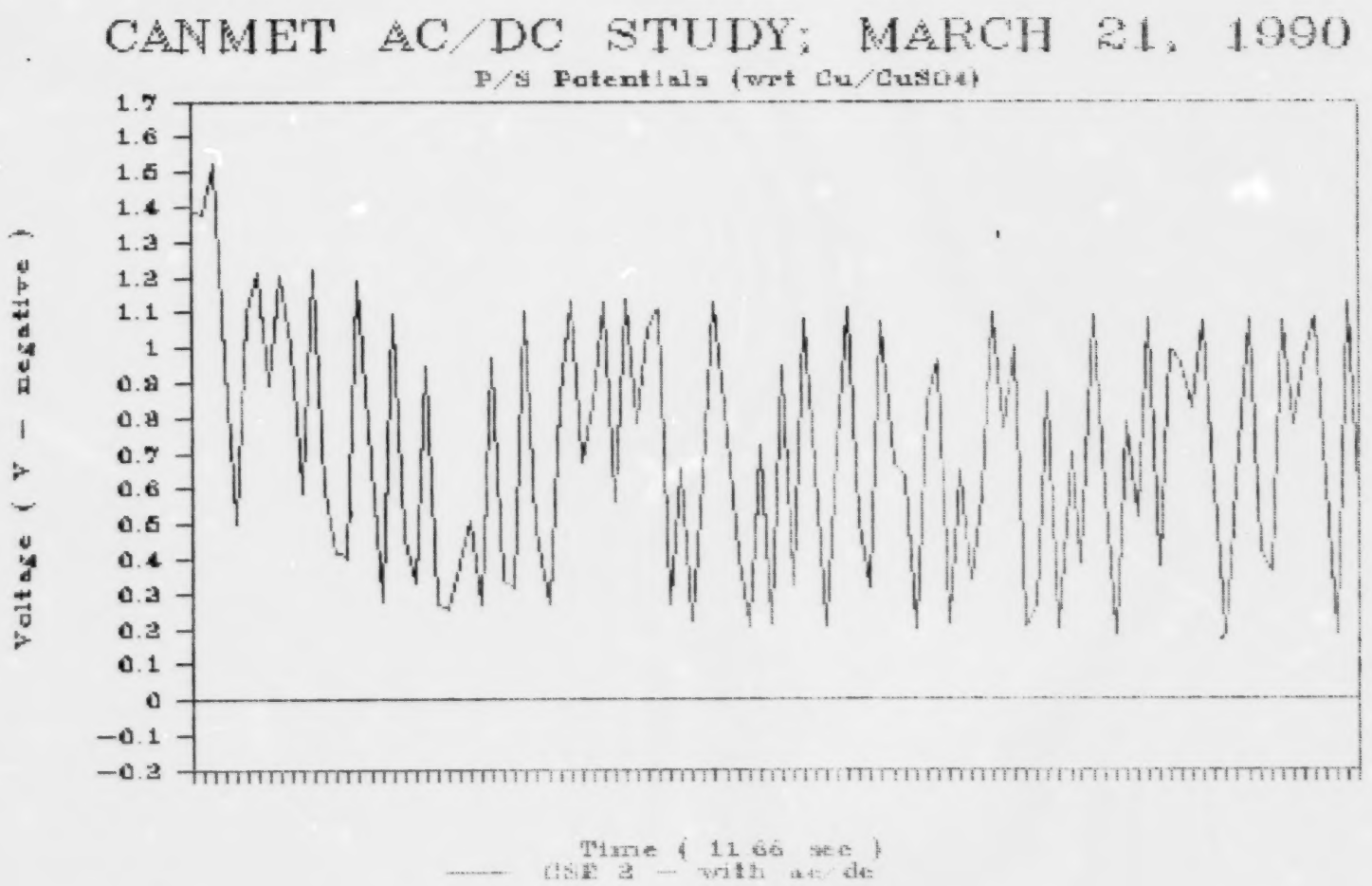


Figure 16

Identified on Summary of Data (Appendix L)

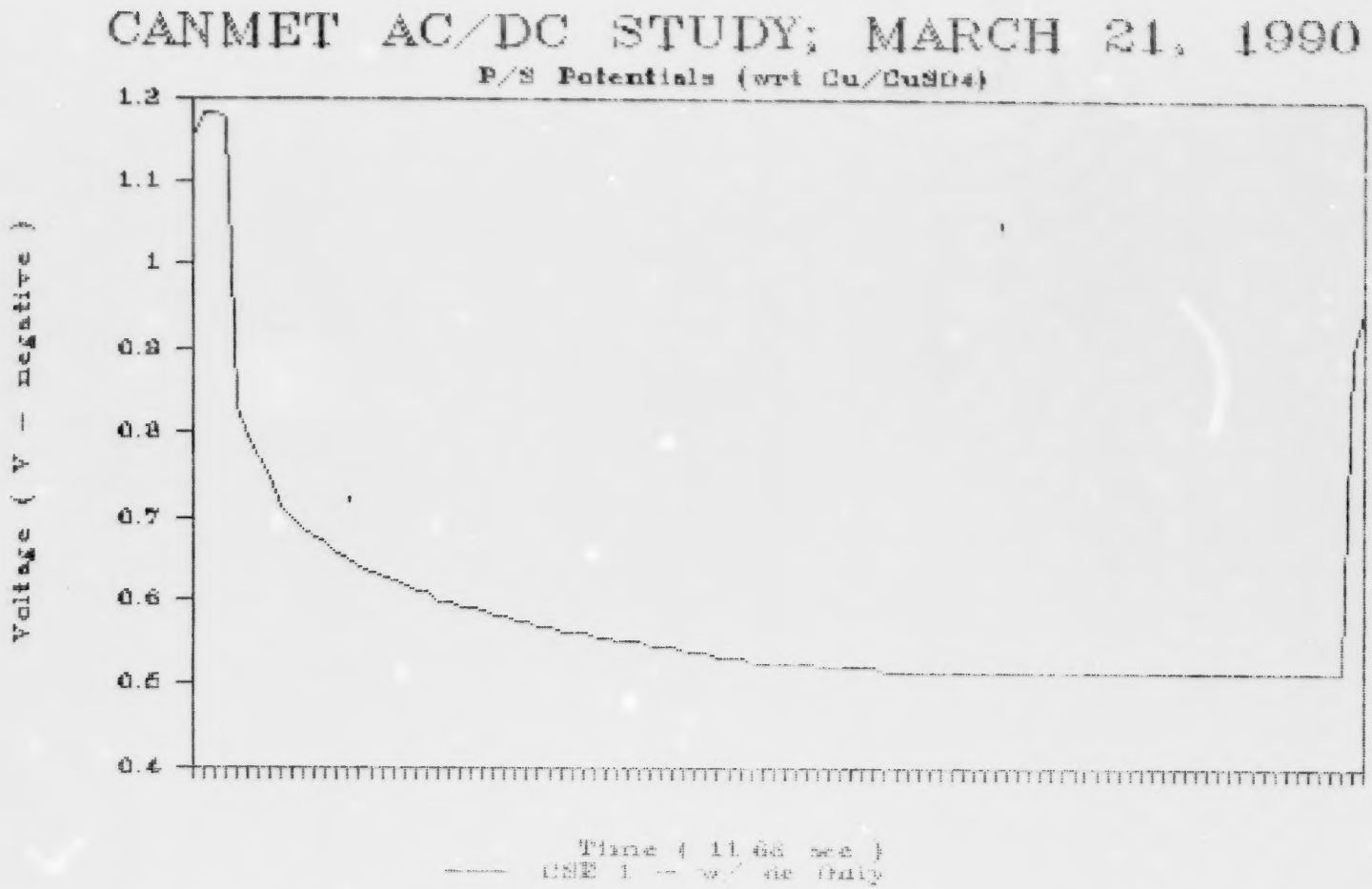


Figure 17

Identified on Summary of Data (Appendix L)

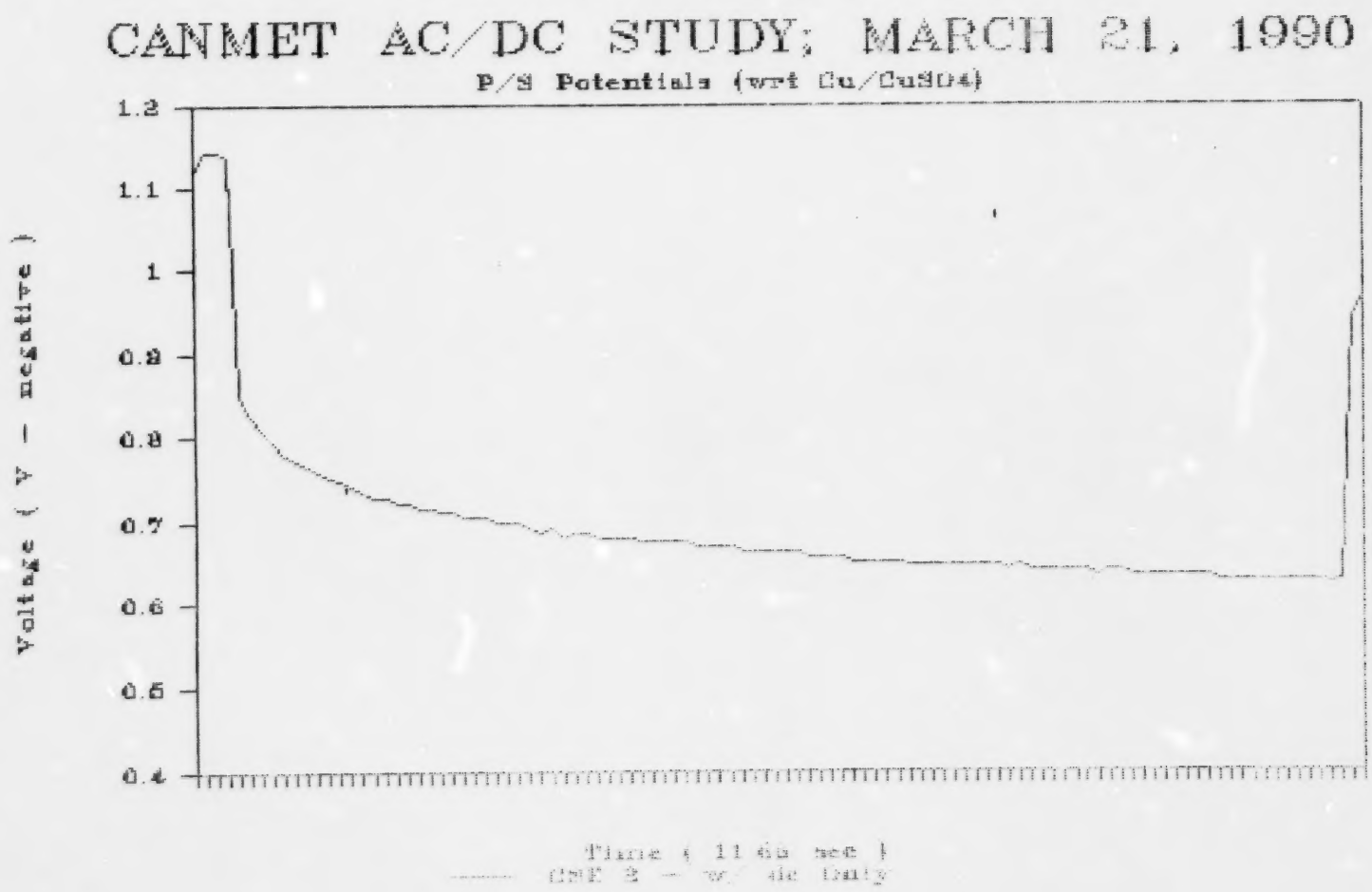


Figure 18

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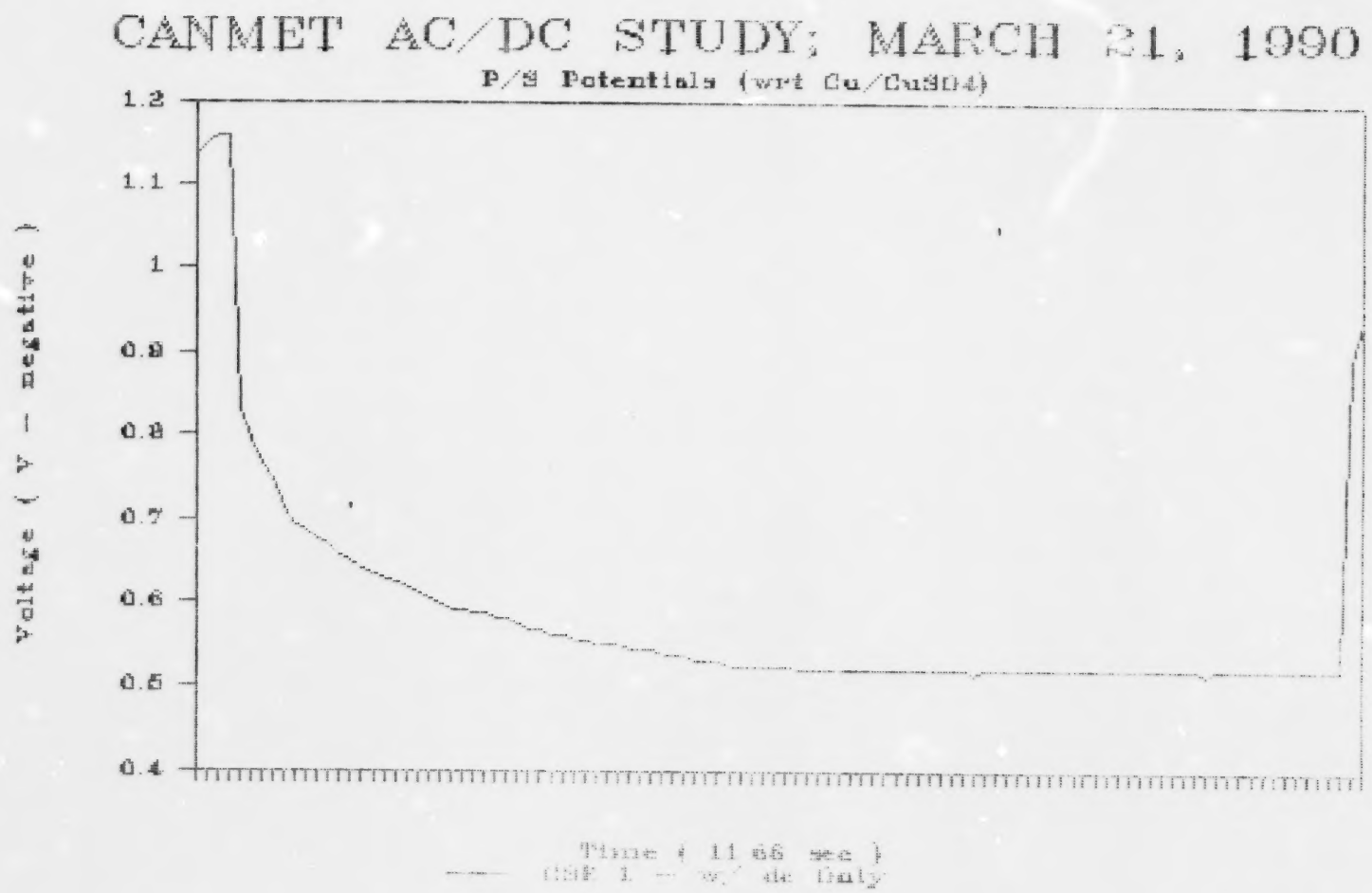
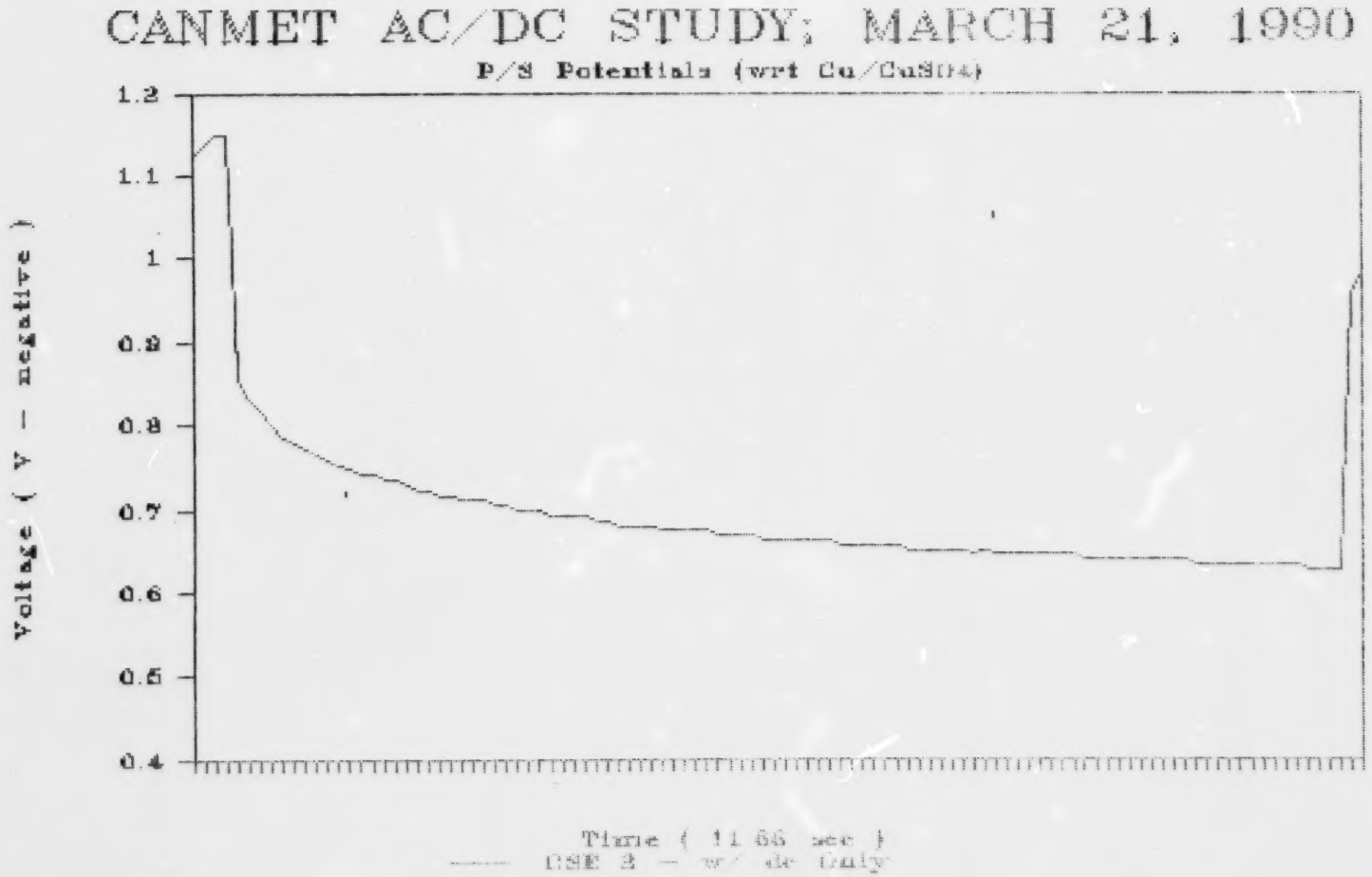


Figure 19

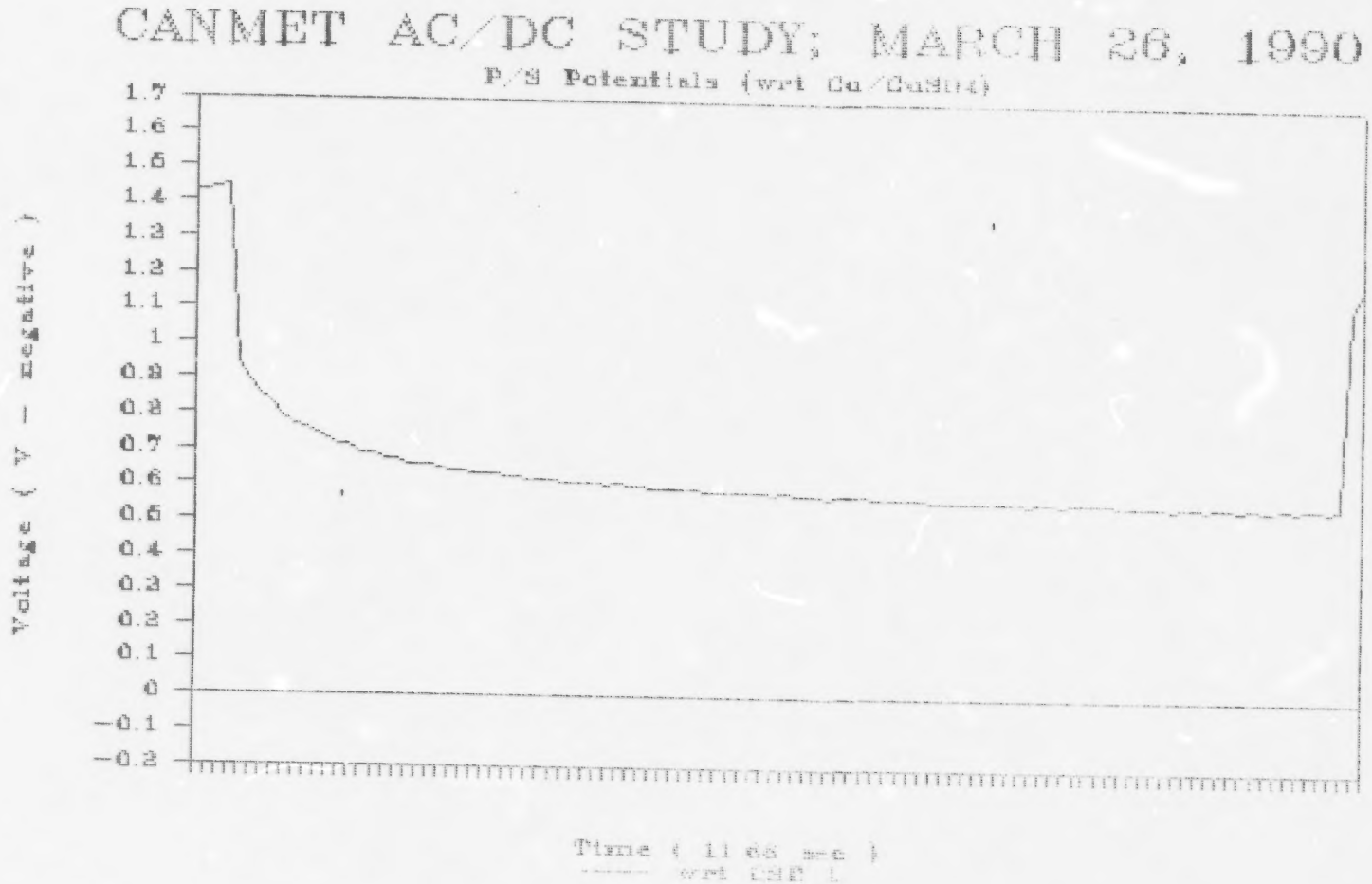
Identified on Summary of Data (Appendix L)



Meter Reading Prior to dc Off: Structure 1 to Reference = -1.424 V dc

dc Current to Structure 1 = 3.09 mA

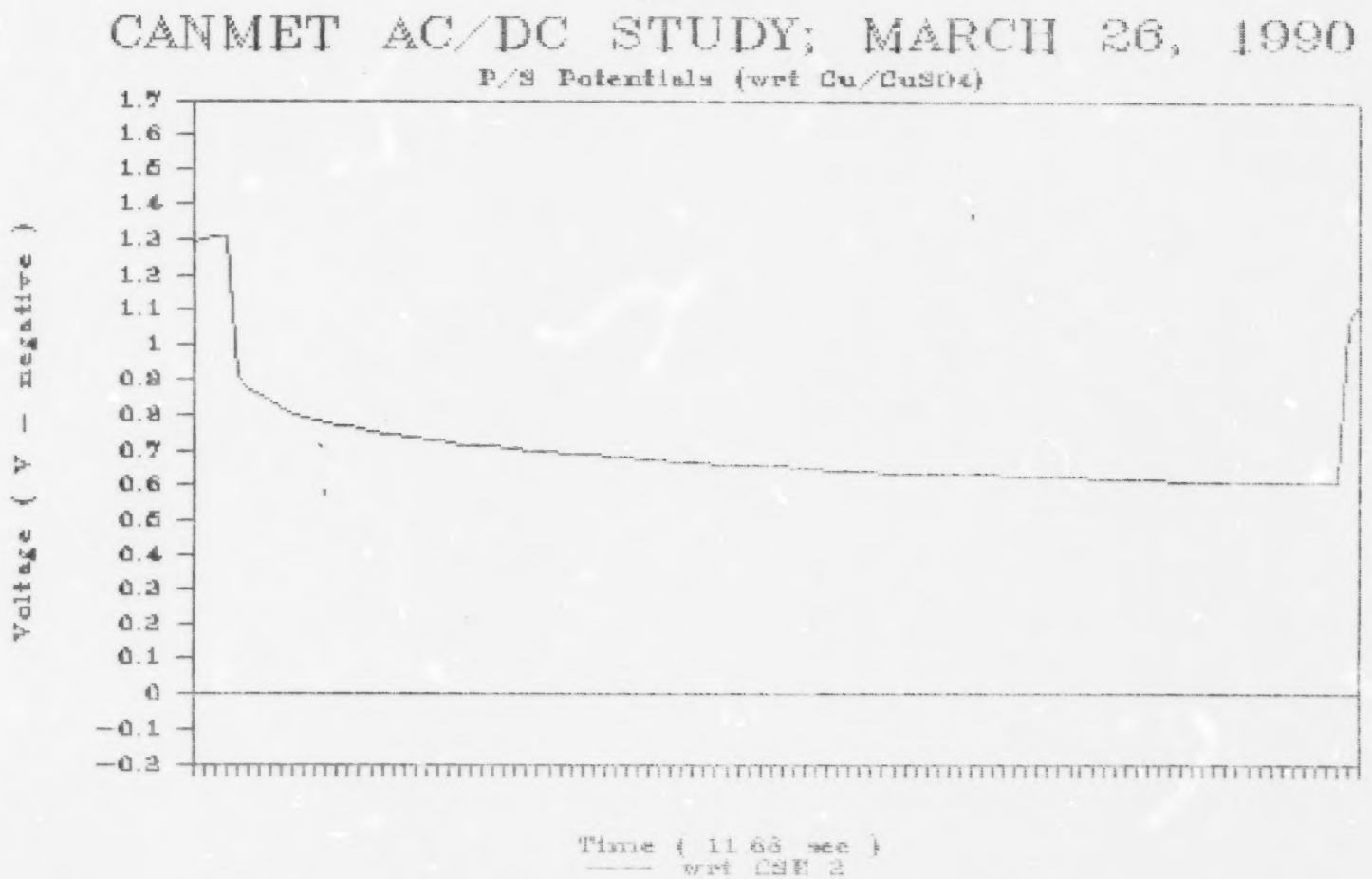
Figure 20



Meter Reading Prior to dc Off: Structure 2 to Reference = 1.250 V dc

dc Current to Structure 2 = 2.61 mA dc

Figure 21

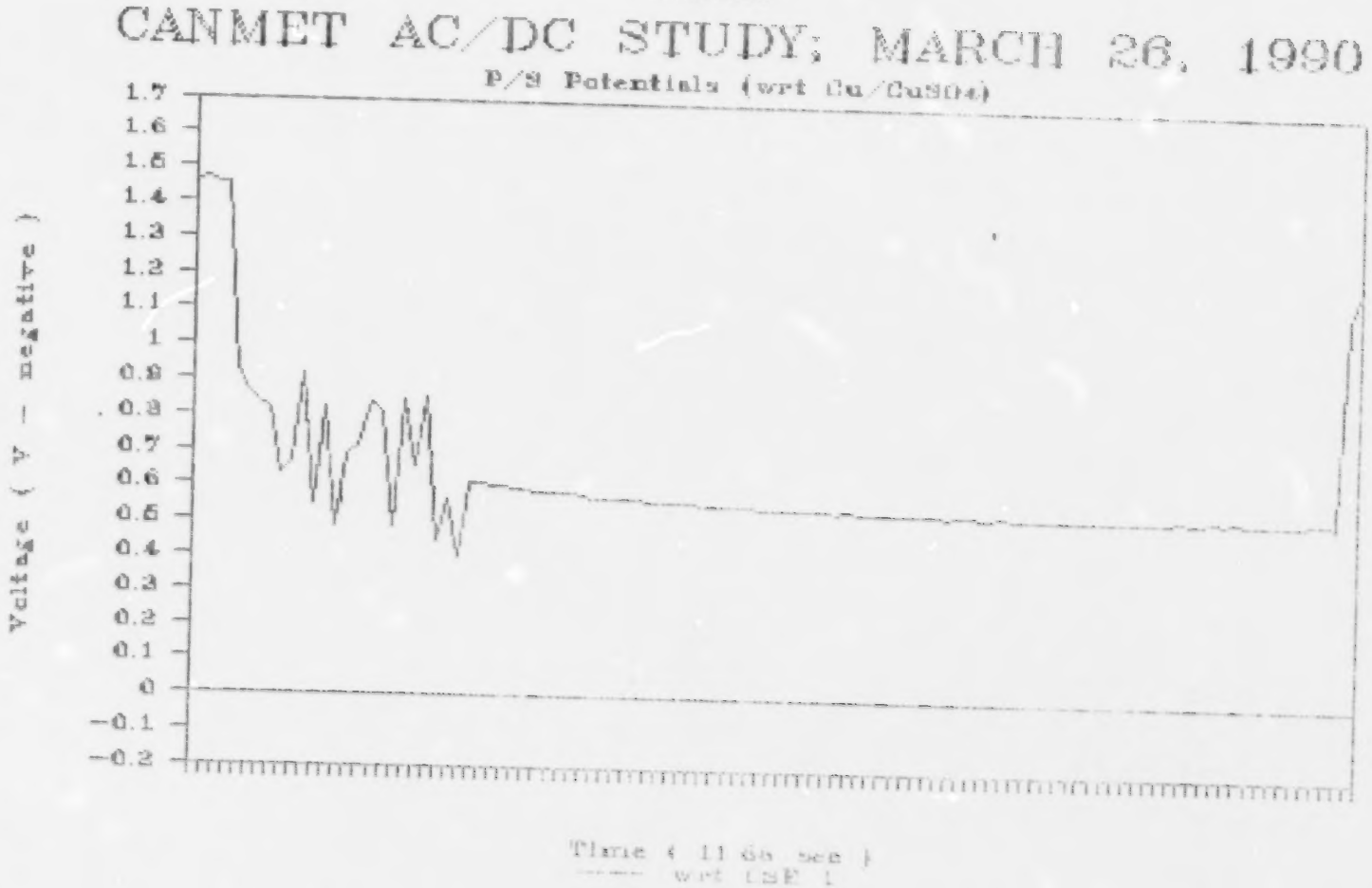


Meter Readings: dc values, see figure 10

Applied ac Voltage = 2.52 V ac

ac Current to Structure 1 = 1.81 mA ac

Figure 22

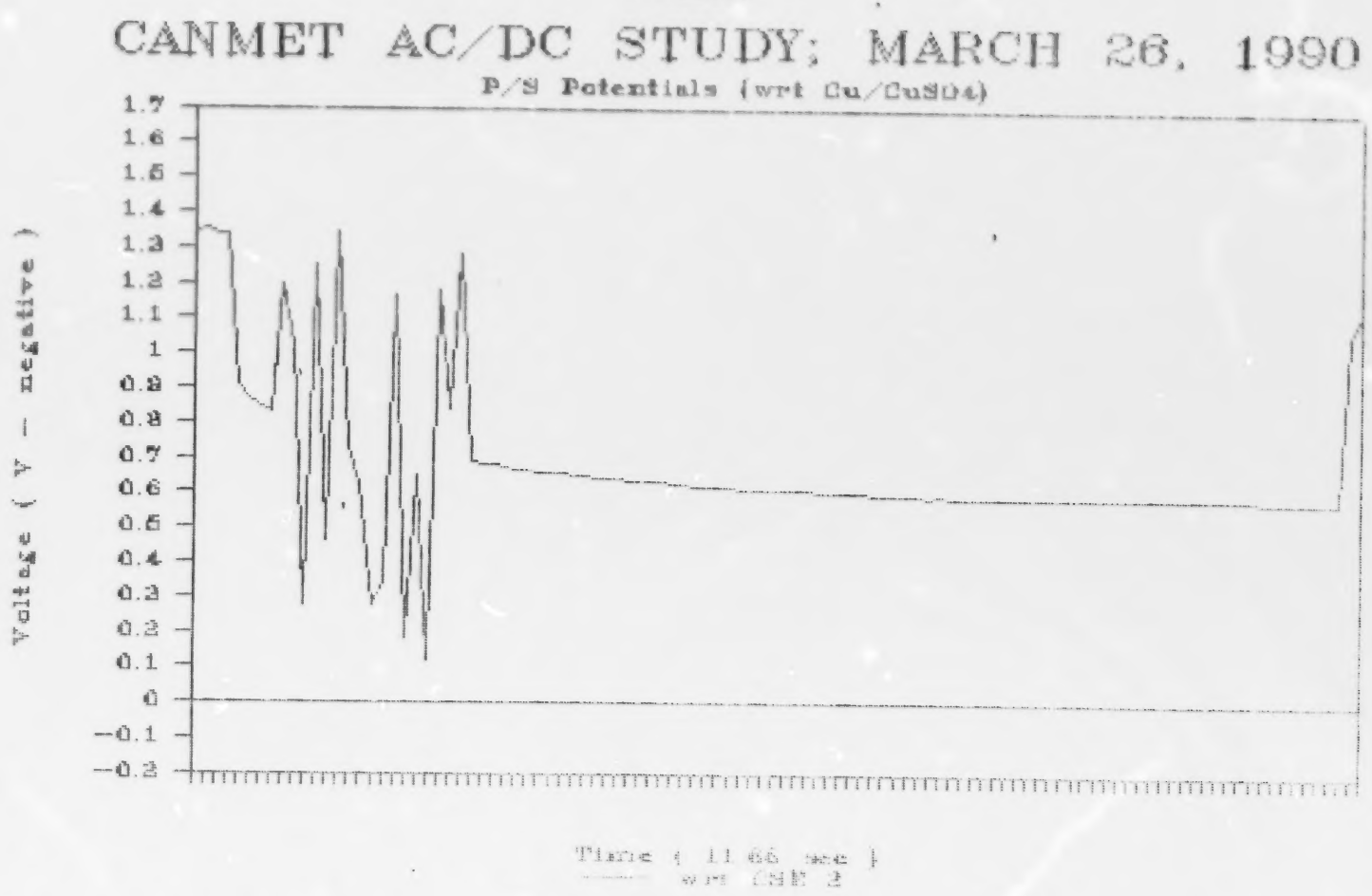


Meter Readings: dc values, see figure 10

Applied ac Voltage = 2.52 V ac

ac Current to Structure 2 = 1.81 mA ac

Figure 23

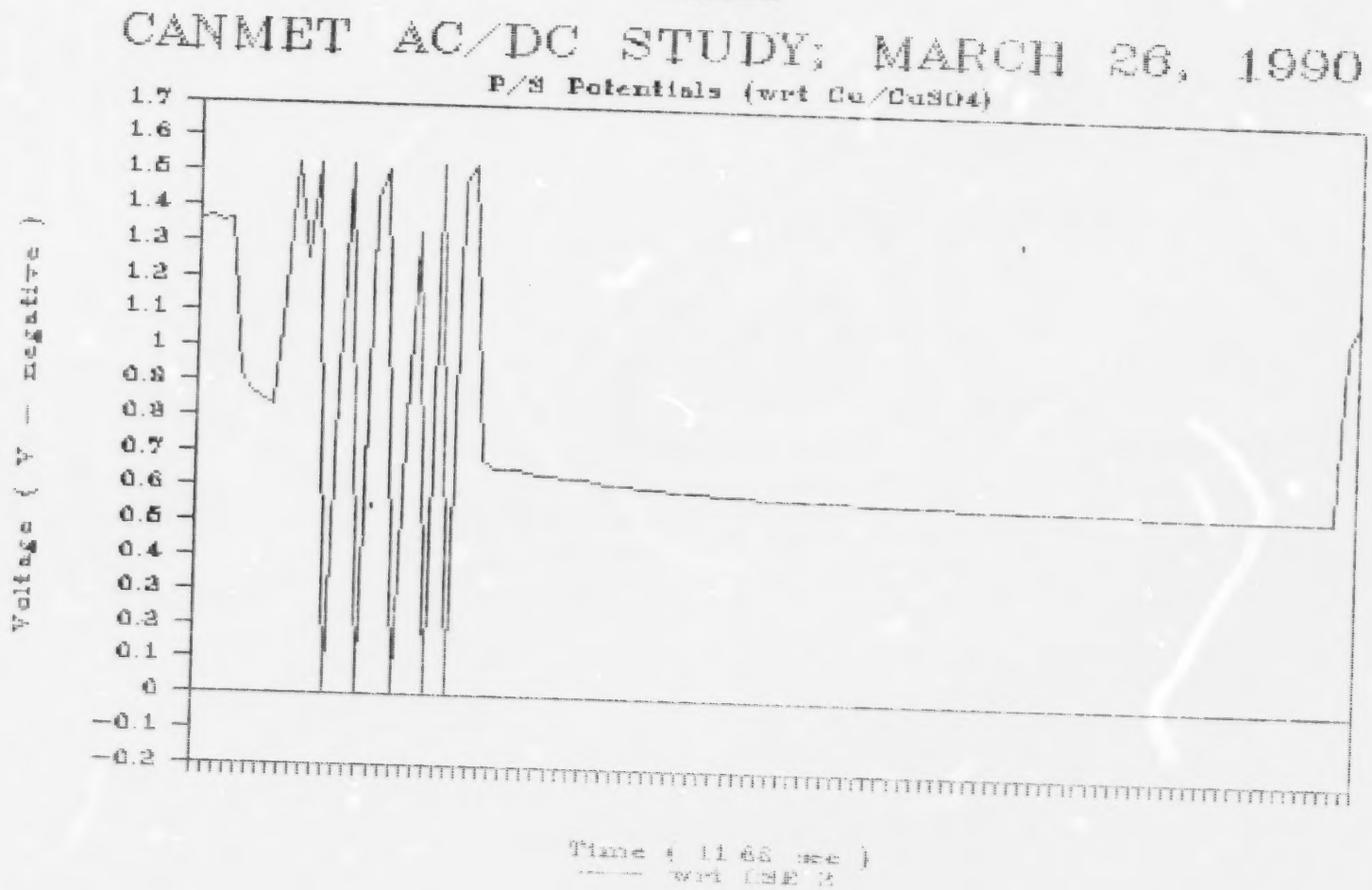


Meter Readings, dc On; ac On: dc values, see figure 12

Applied ac Voltage = 4.75 V ac

ac Current to Structure 2 = 3.5 mA ac

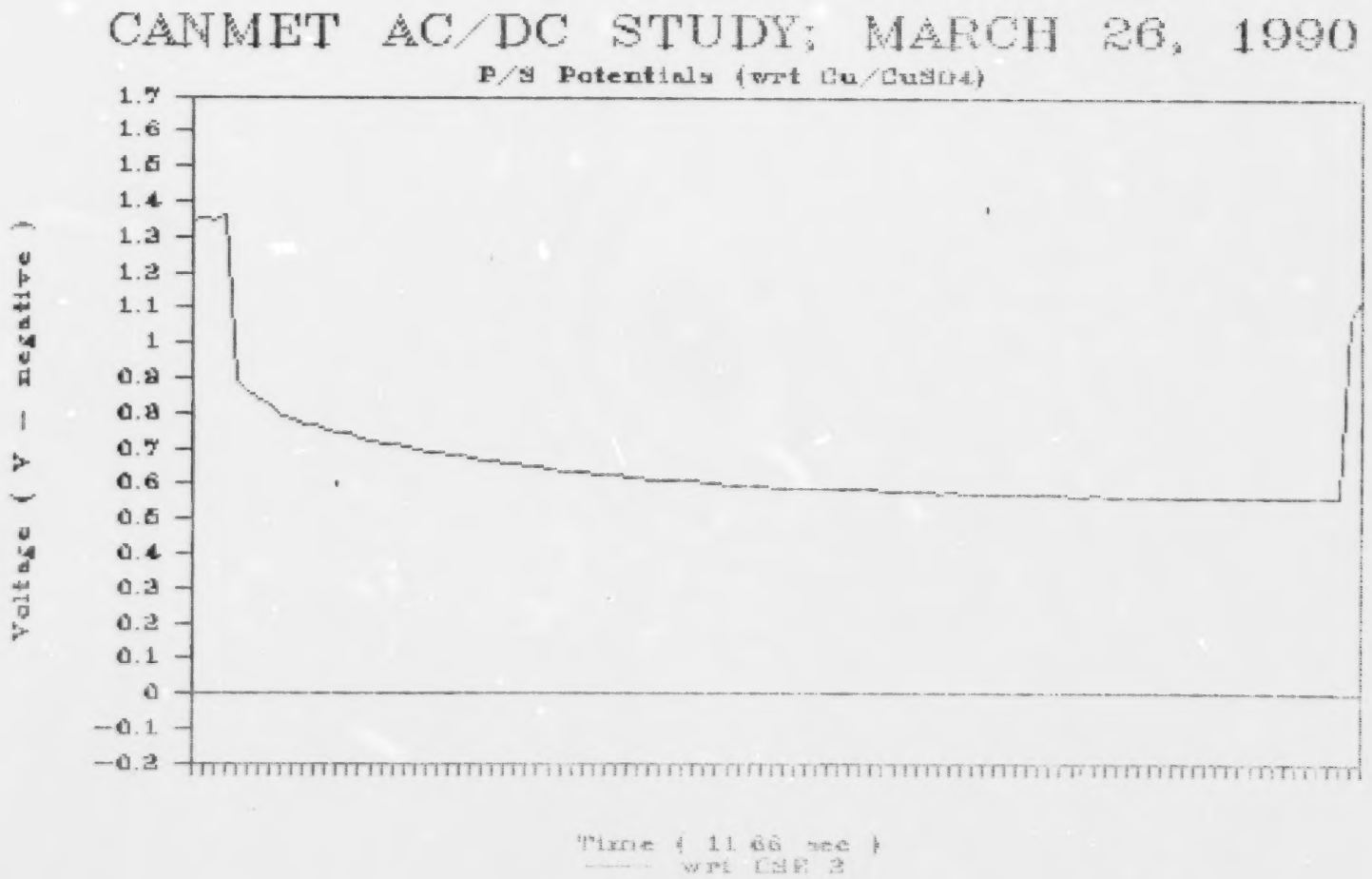
Figure 24



Meter Readings, dc On; ac Off: Structure 2 to Reference = -1.250 V dc

dc Current to Structure 2 = 2.61 mA dc

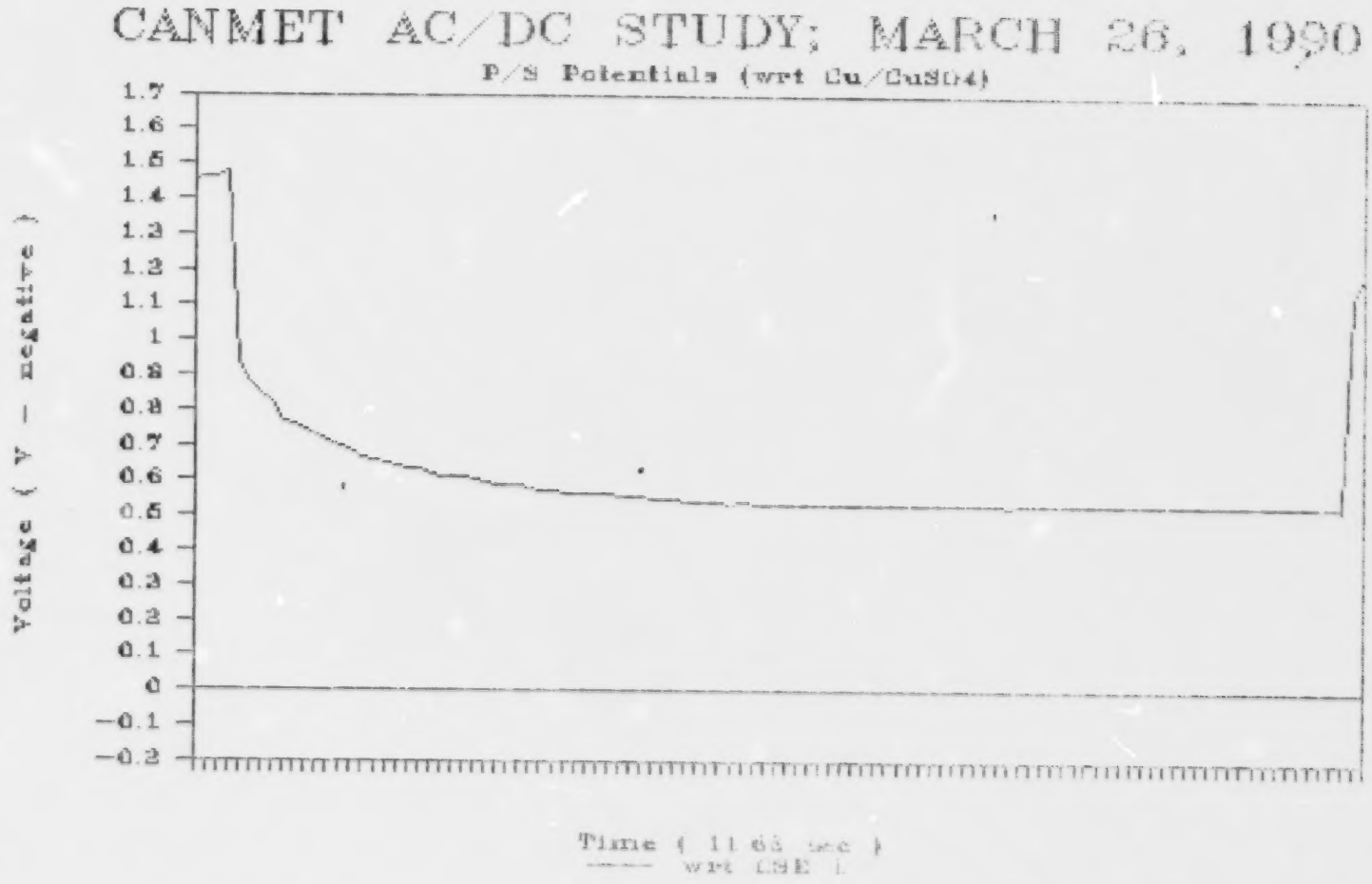
Figure 25



Meter Readings Prior to dc Off: Structure 1 to Reference = -1.424 V dc

dc Current to Structure 1 = 3.09 mA dc

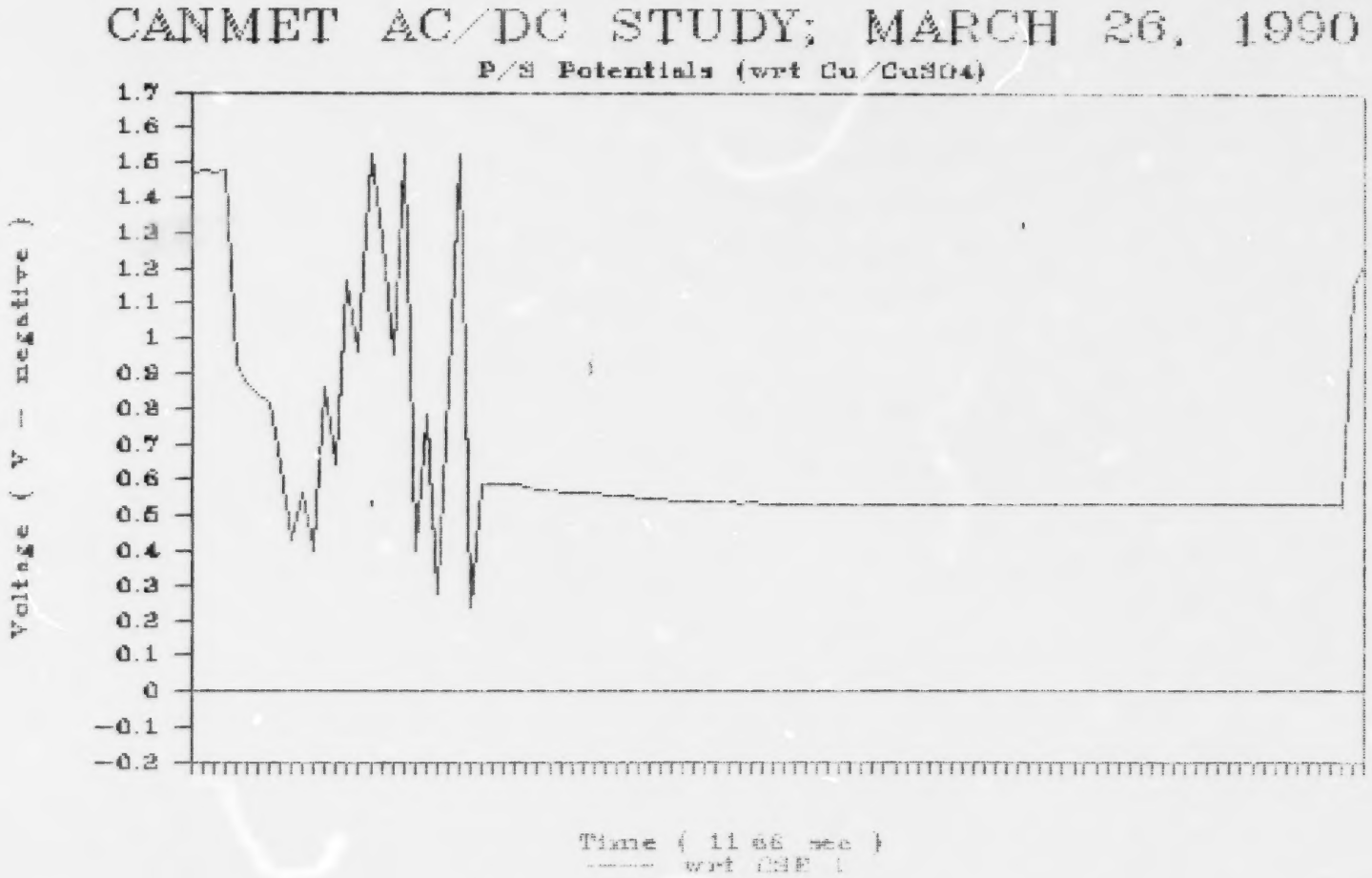
Figure 26



Meter Readings Prior to dc Off: dc values, see figure 12

Applied ac Voltage = 4.75 V ac; ac Current to Structure 1 = 3.5 mA ac

Figure 27



EPILOGUE

Further study is warranted to bring this research and development program to its appropriate conclusion. It was originally proposed to make at least one or two local trial field applications; then having addressed known-problem areas, it was proposed to devise the special tooling and equipment required to cost-effectively achieve a uniform polarized potential at the surface of other underground tanks and buried piping facilities.

However, unexpected difficulties were encountered in accomplishing both key objectives - to determine the chemistry of a slurry for existing facilities, and of a superior granular backfill for new underground steel storage tanks and piping structures. In our determination to achieve these initial research goals, the originally authorized budget was far exceeded during March/April 1990 in the final analysis; therefore neither any budget nor clement weather remained to conduct any field tests whatsoever, although the research work was successful. Accordingly, it is suggested that a development program should be authorized.

Furthermore, several interesting side-effects were observed during the course of this study. The titanium heteroxide anodes appeared to attract moisture to the surface and to withstand the electrochemistry of the transformed environment, whereas the graphite anodes disintegrated prematurely in this highly alkaline environment. Also the application of tannin to convert

(Epilogue cont'd)

a rusted steel surface, resulted in a very low current density requirement. The induced and a.c. stray current interference problems, especially those at the higher energy levels prevalent to well coated electrically isolated pipelines, should be investigated, insofar as a.c. has been known to accelerate d.c. corrosion, and/or to reduce or nullify cathodic polarization.

Proposed Resolution of the Many Unusual Types of Problems Encountered by a Recommended Development Program

The attached schematic diagrams show the underground diesel standby tank storage system at Mt. Hope (Hamilton) International Airport. This system was designed and installed to conduct a research program. It was proposed to investigate;

- the need to isolate tanks from hold down straps, and the hold down straps from contact to the steel reinforcing in the concrete slab,

- the performance of the zinc anodes on the tanks, and the zinc and magnesium anodes for the buried piping,

However, it was found that whereas all electrically isolated structures, cathodically protected at fully polarized potentials, that;

- stray d.c. current interference was significant, and,

- over 20 volts d.c. was necessary to apply the 2 mA protective current required to polarize the surface of the produce piping.

This is one of the many problems found in about 40 years in surveying and designing cathodic protection systems for underground tanks.

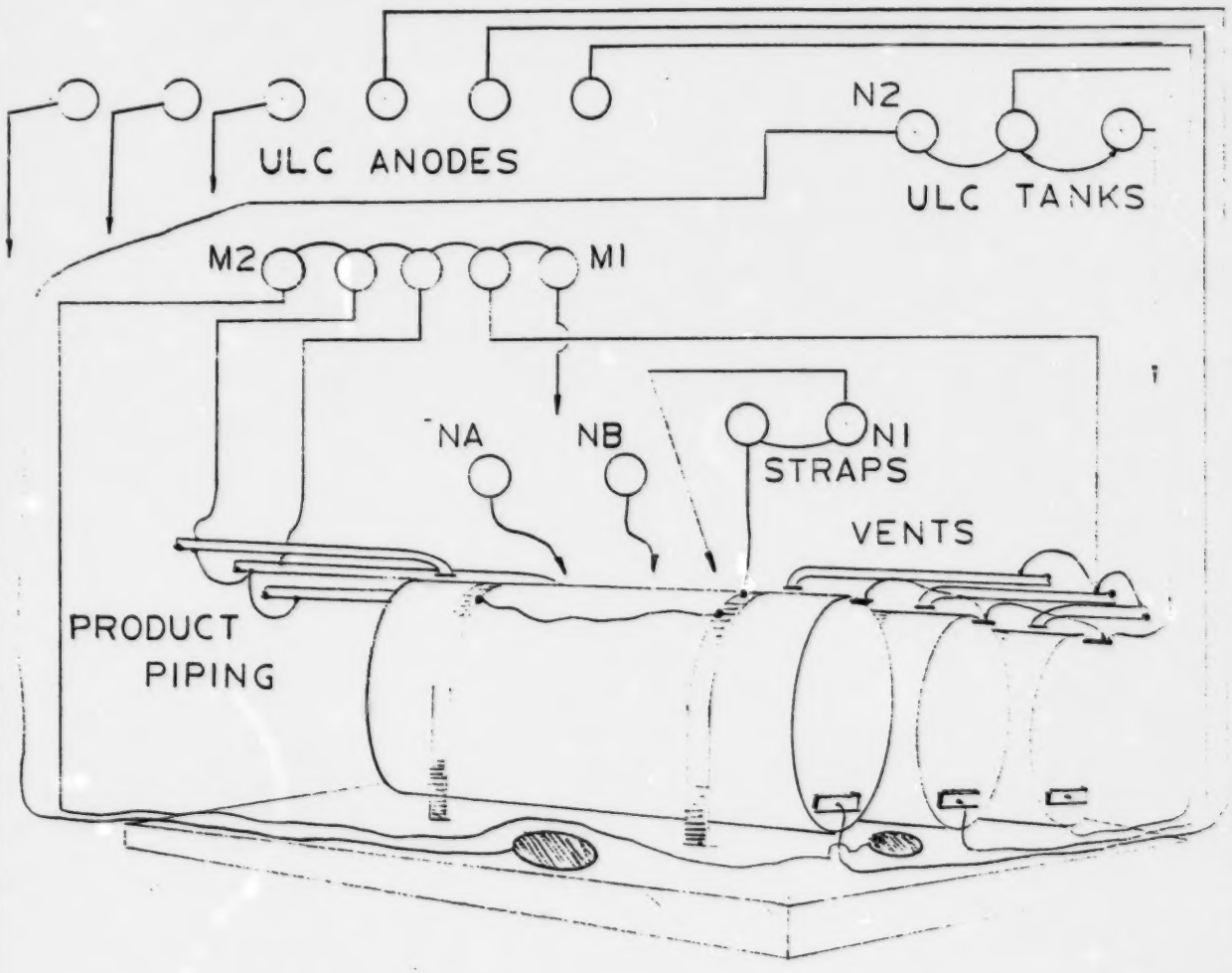


FIGURE 1: ULC TANK TEST INSTALLATION

INTERPROVINCIAL
CORROSION
CONTROL
COMPANY LIMITED
BURLINGTON ONTARIO CANADA

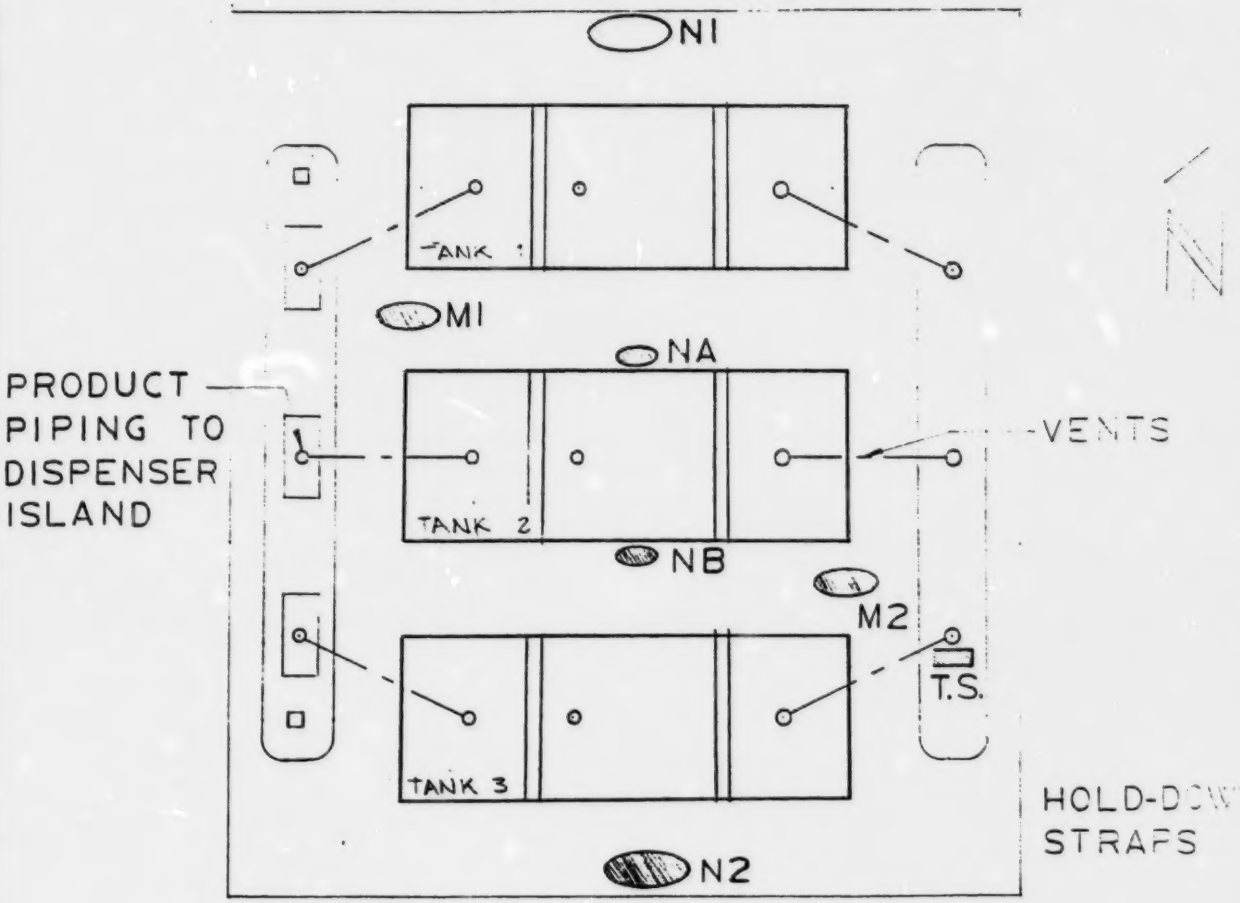
NOVEMBER, 1987

DS.

ULC TANK INSTALLATION: MT. HOPE AIRPORT

CATHODIC PROTECTION SYSTEM

LEGEND: T.S. TEST STATION
N1, N2: 30 LB. ZINC ANODES
M1, M2: 17 LB. MAGNESIUM ANODES
NA, NB: ZINC REFERENCES



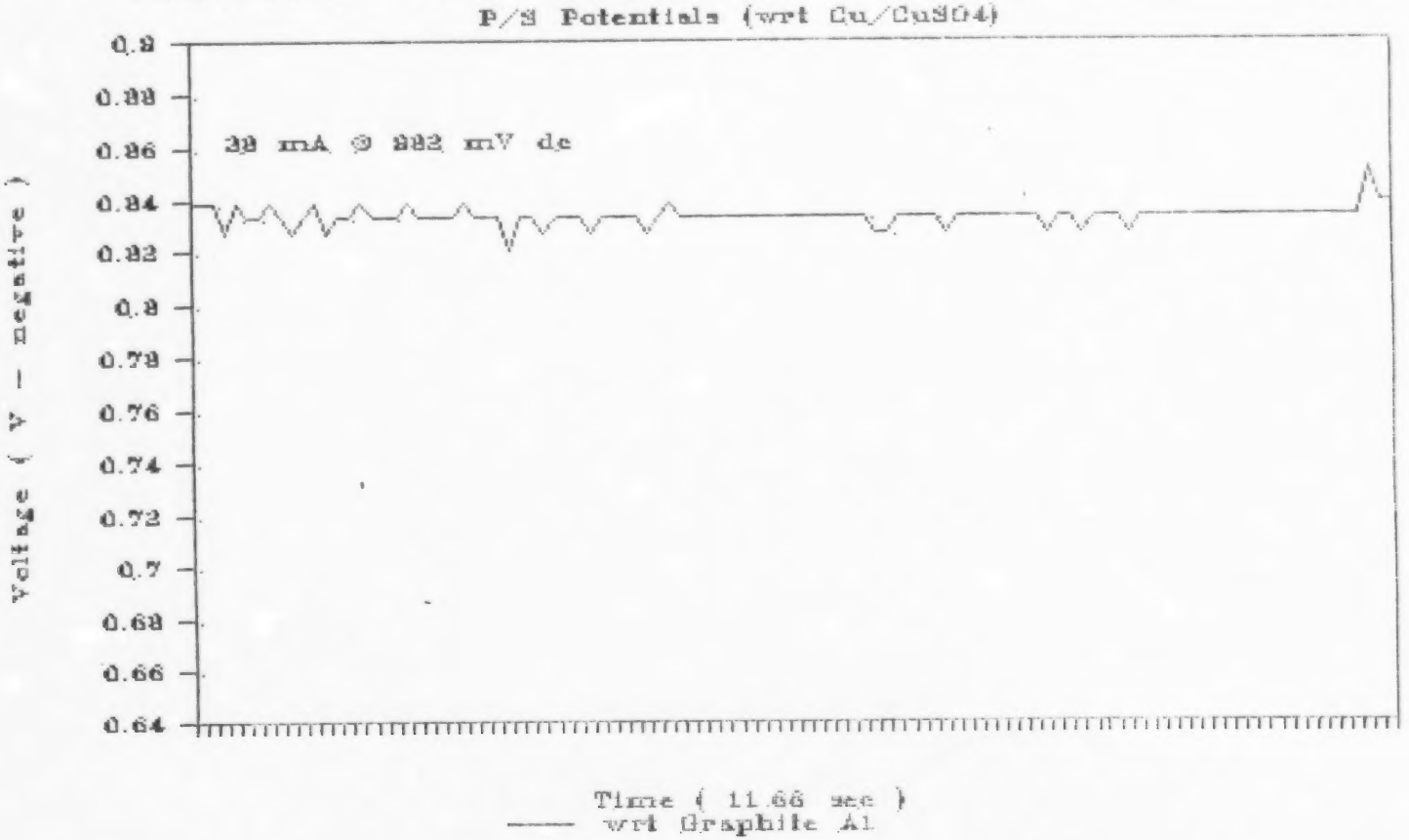
PLAN VIEW
N.T.S.

INTERPROVINCIAL CORROSION CONTROL COMPANY LIMITED

NOVEMBER, 1987 BURLINGTON ONTARIO CANADA

"Depolarization Curves - Graphite Reference A1"

CANMET SPECIMEN # 1; FEB. 27, 1990



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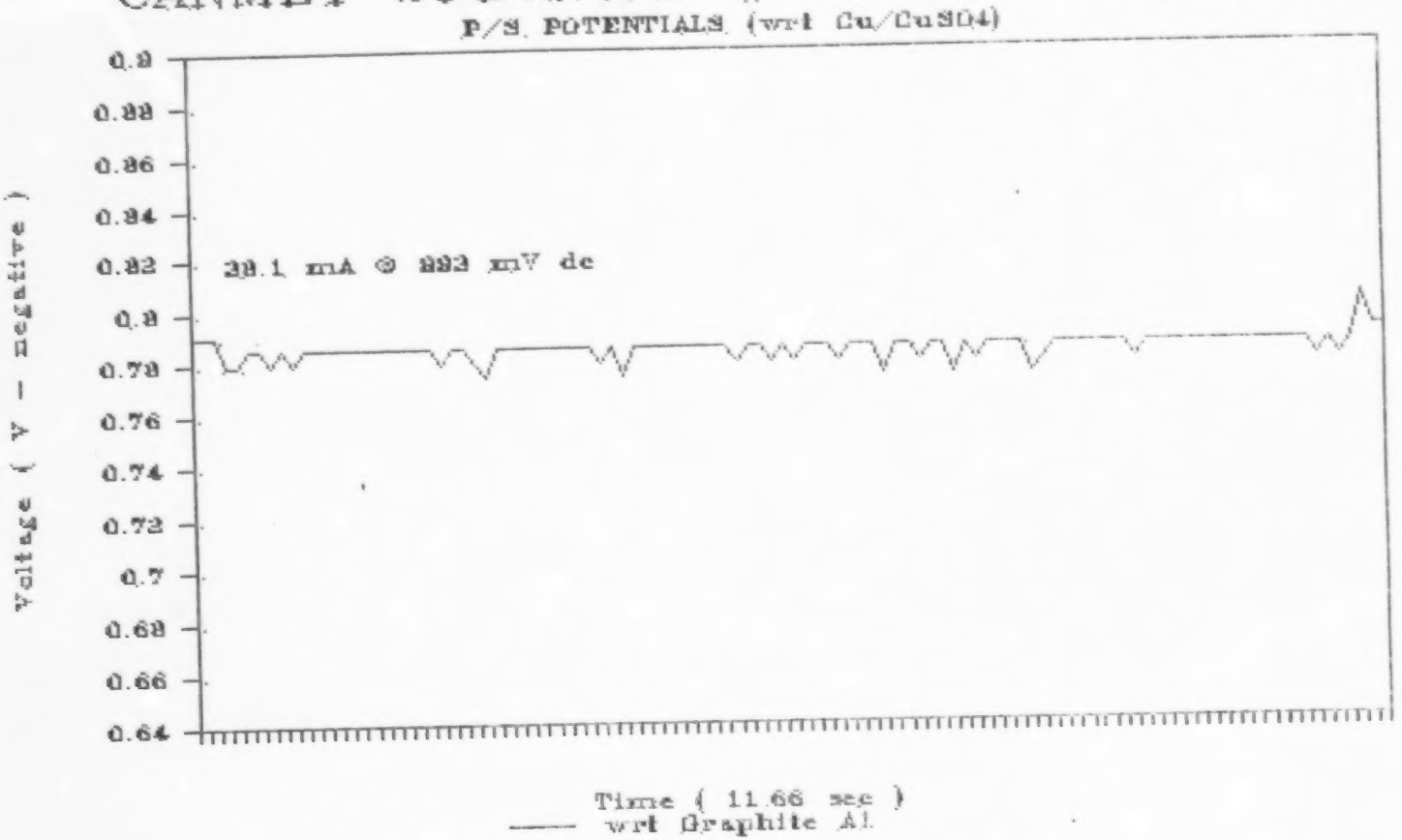
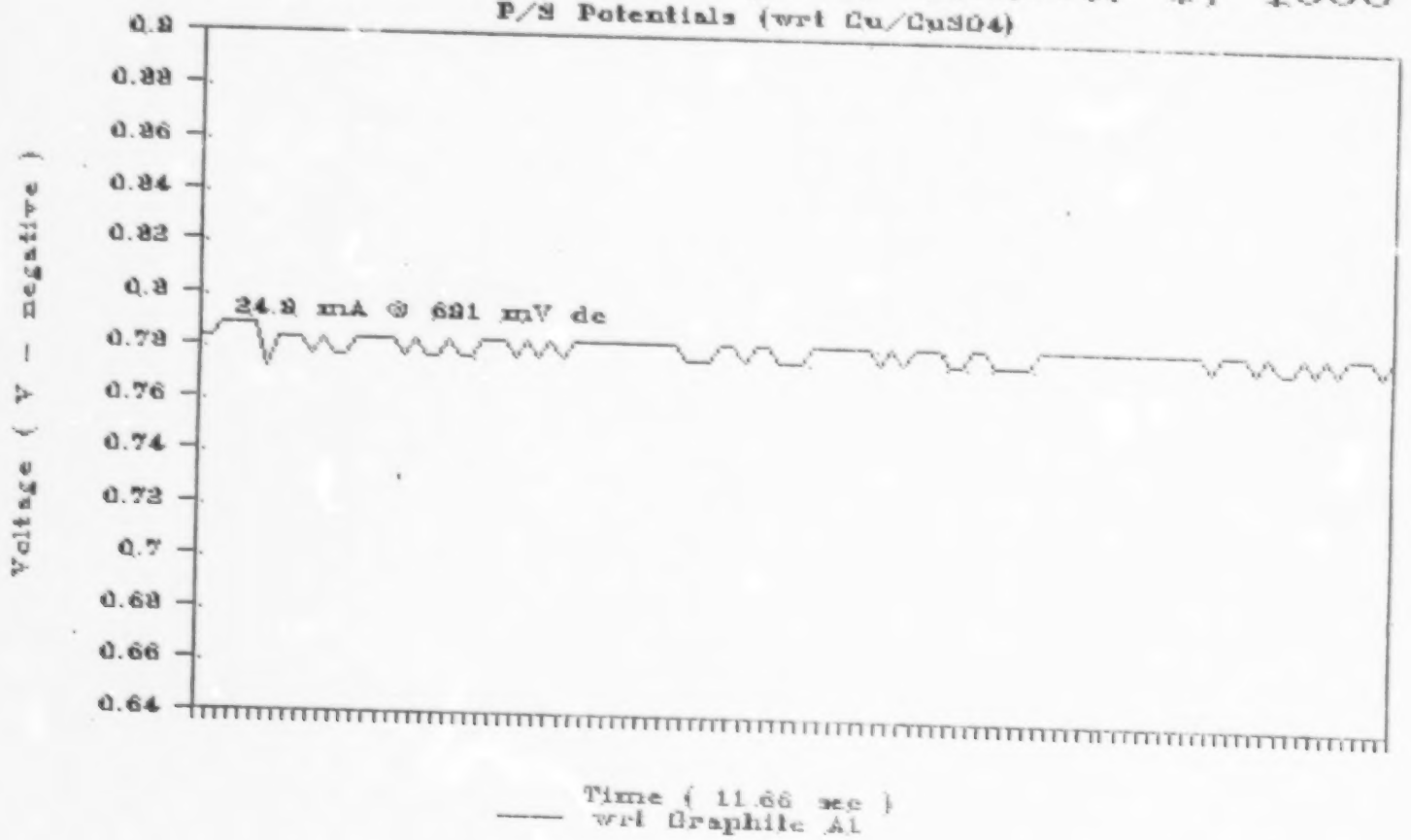


CANMET SPECIMEN # 1; MARCH 1, 1990



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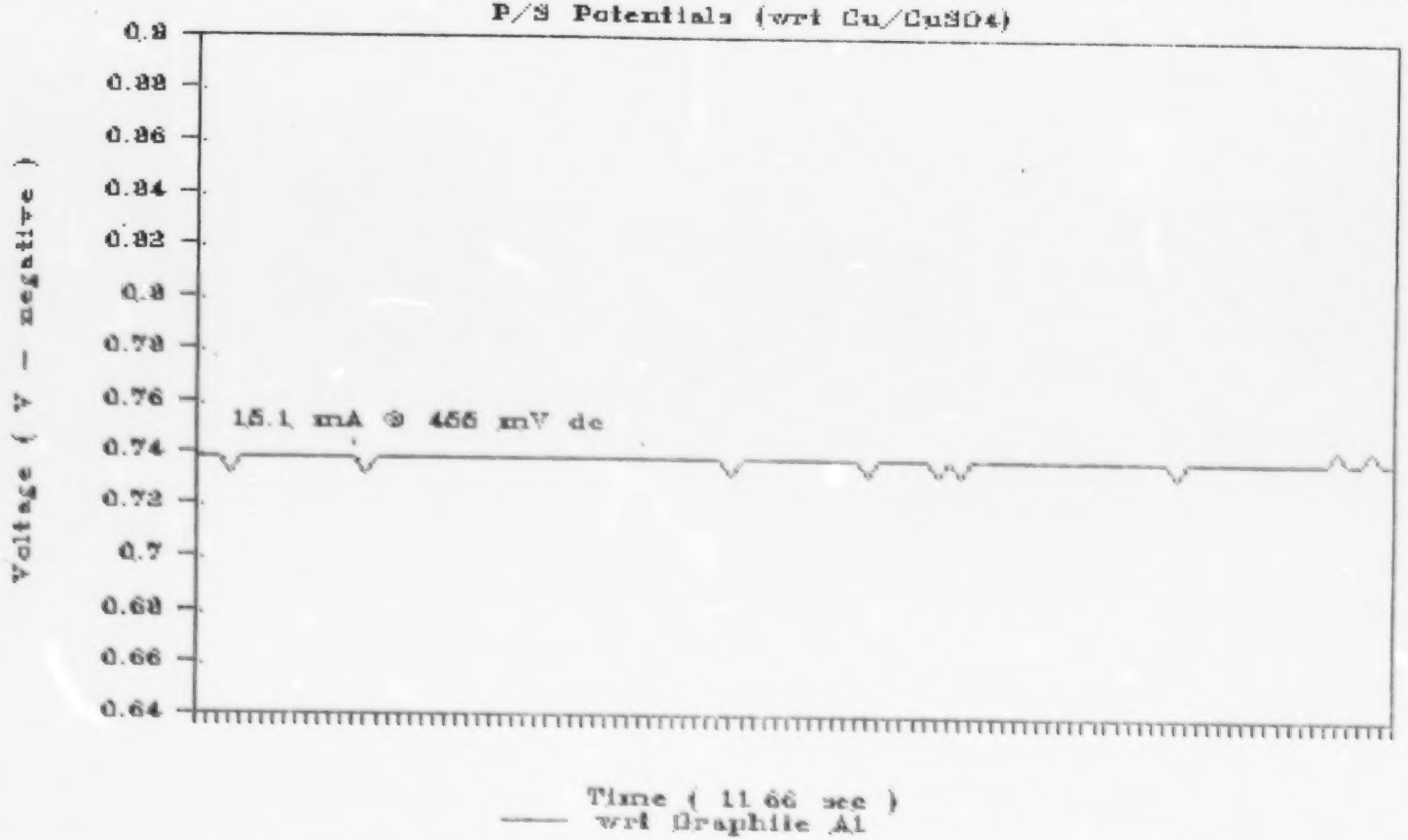
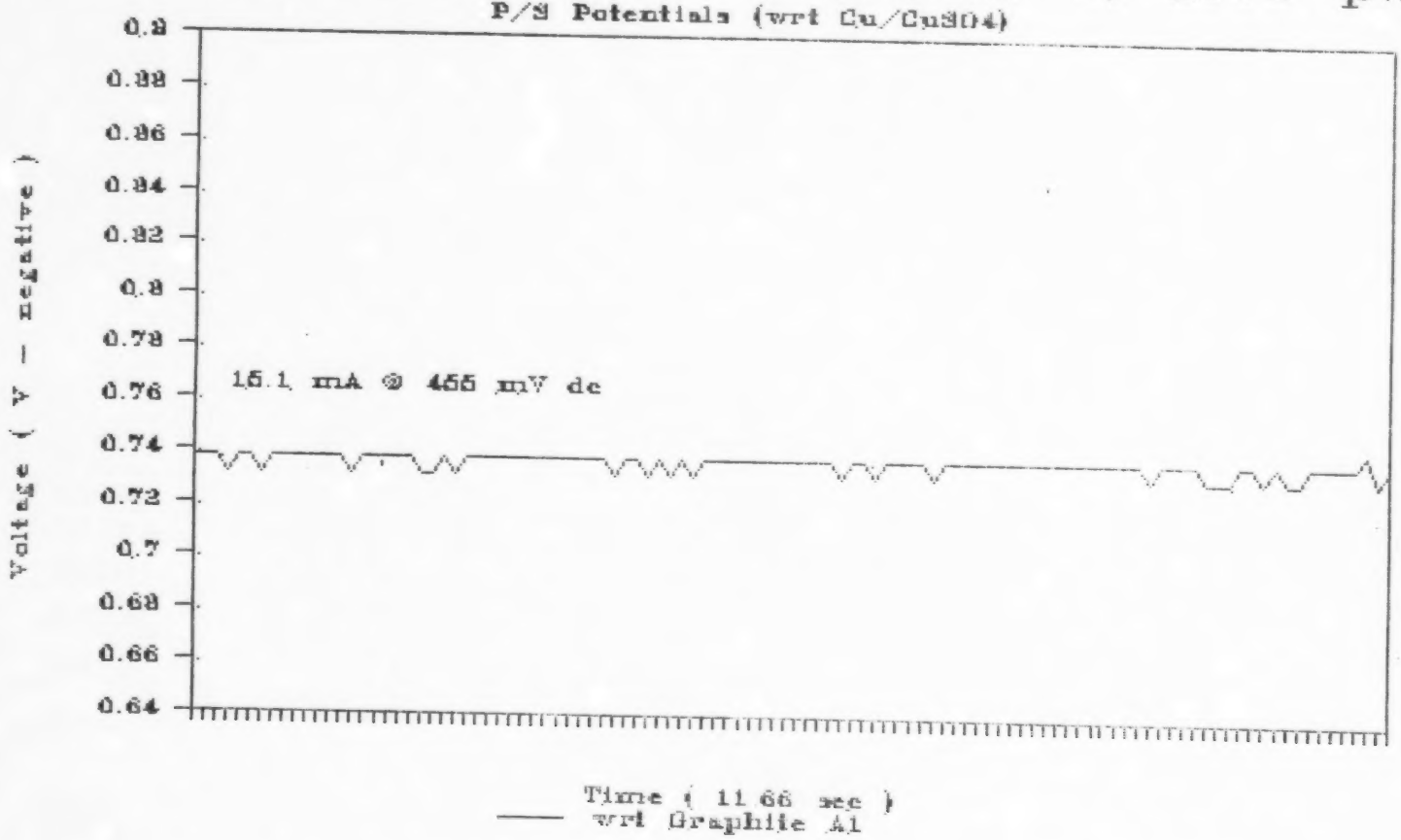
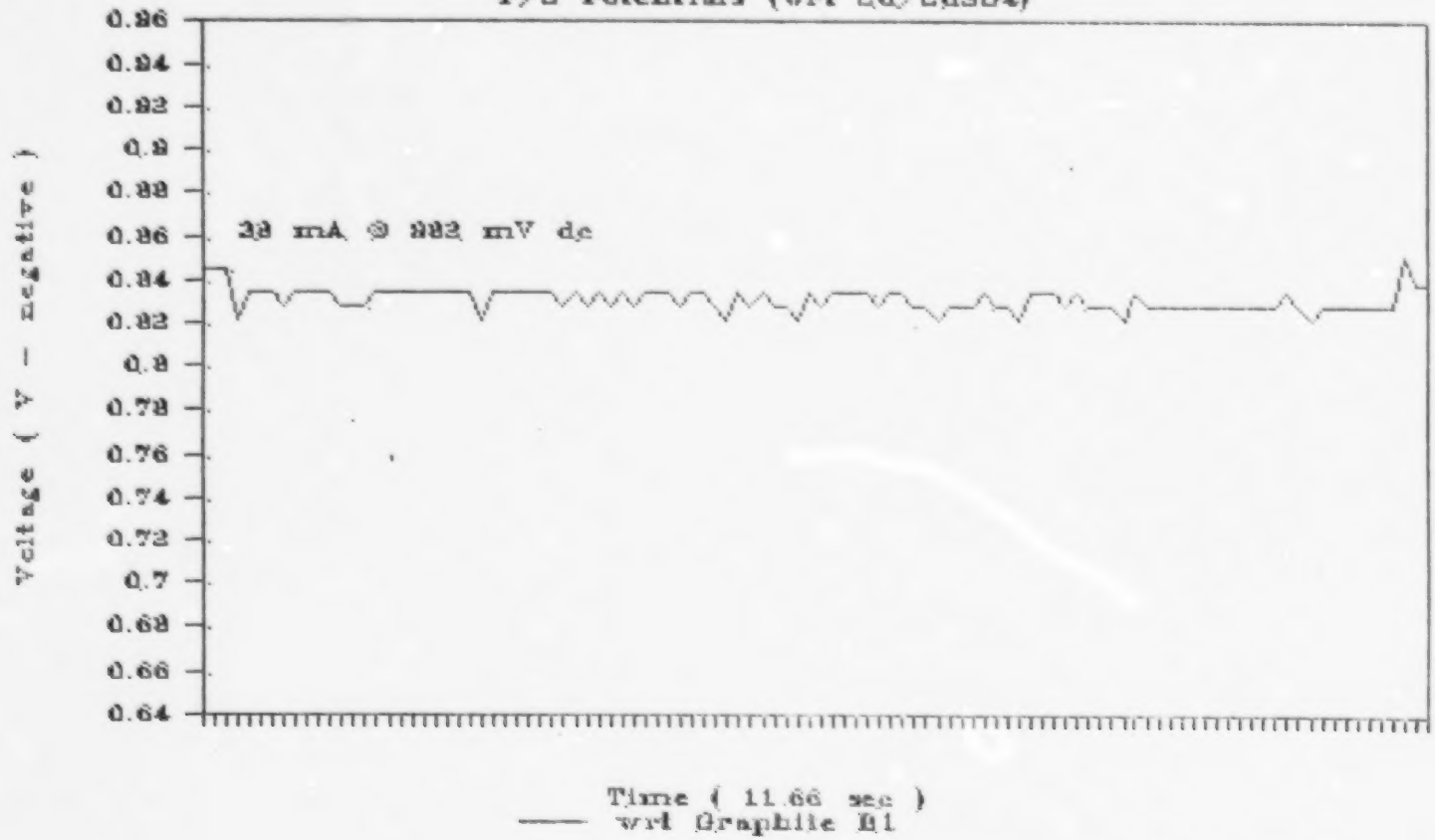


CANMET SPECIMEN # 1; MARCH 2, 1990 p.m.

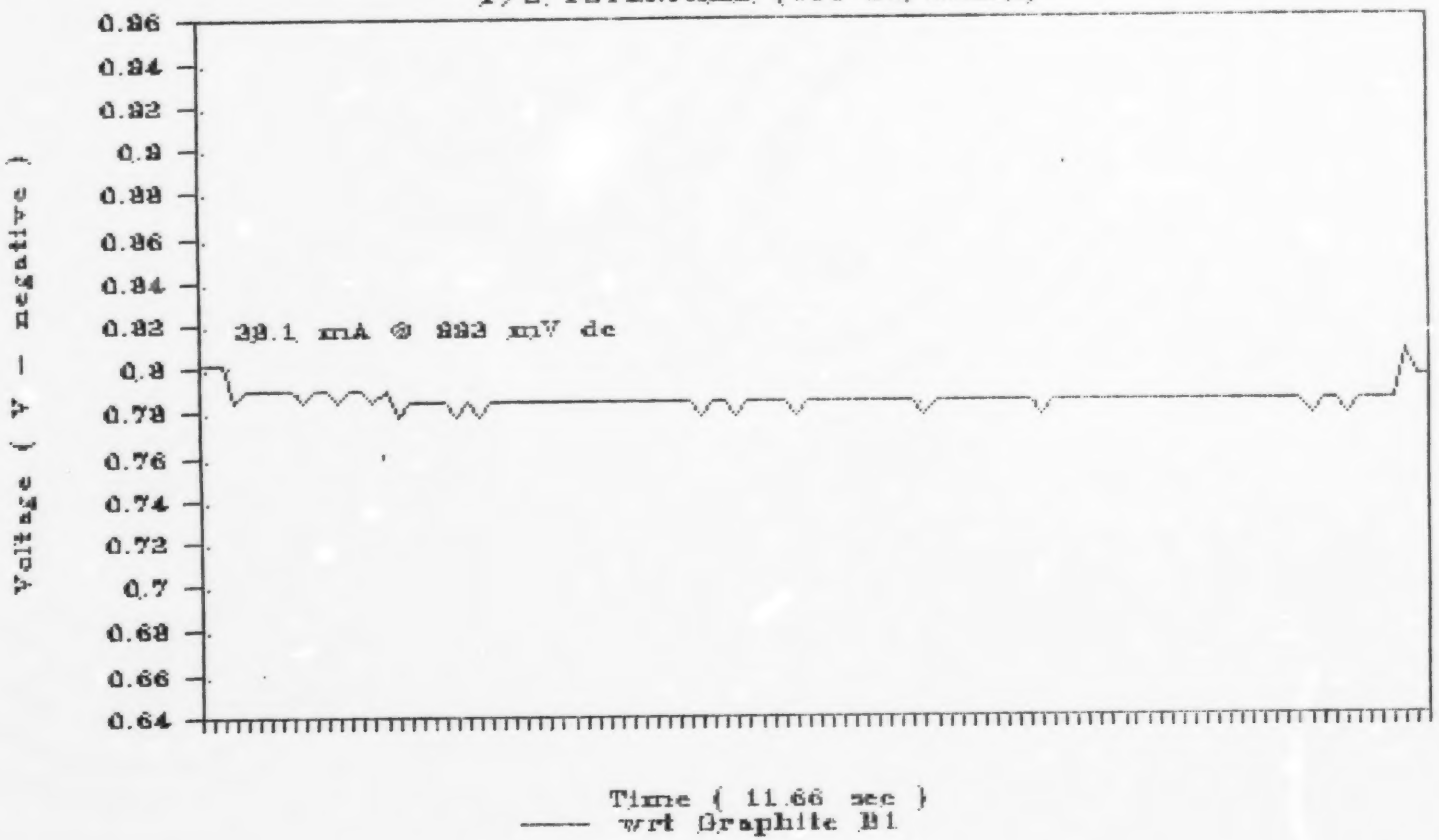


"Depolarization Curves - Graphite Reference B1"

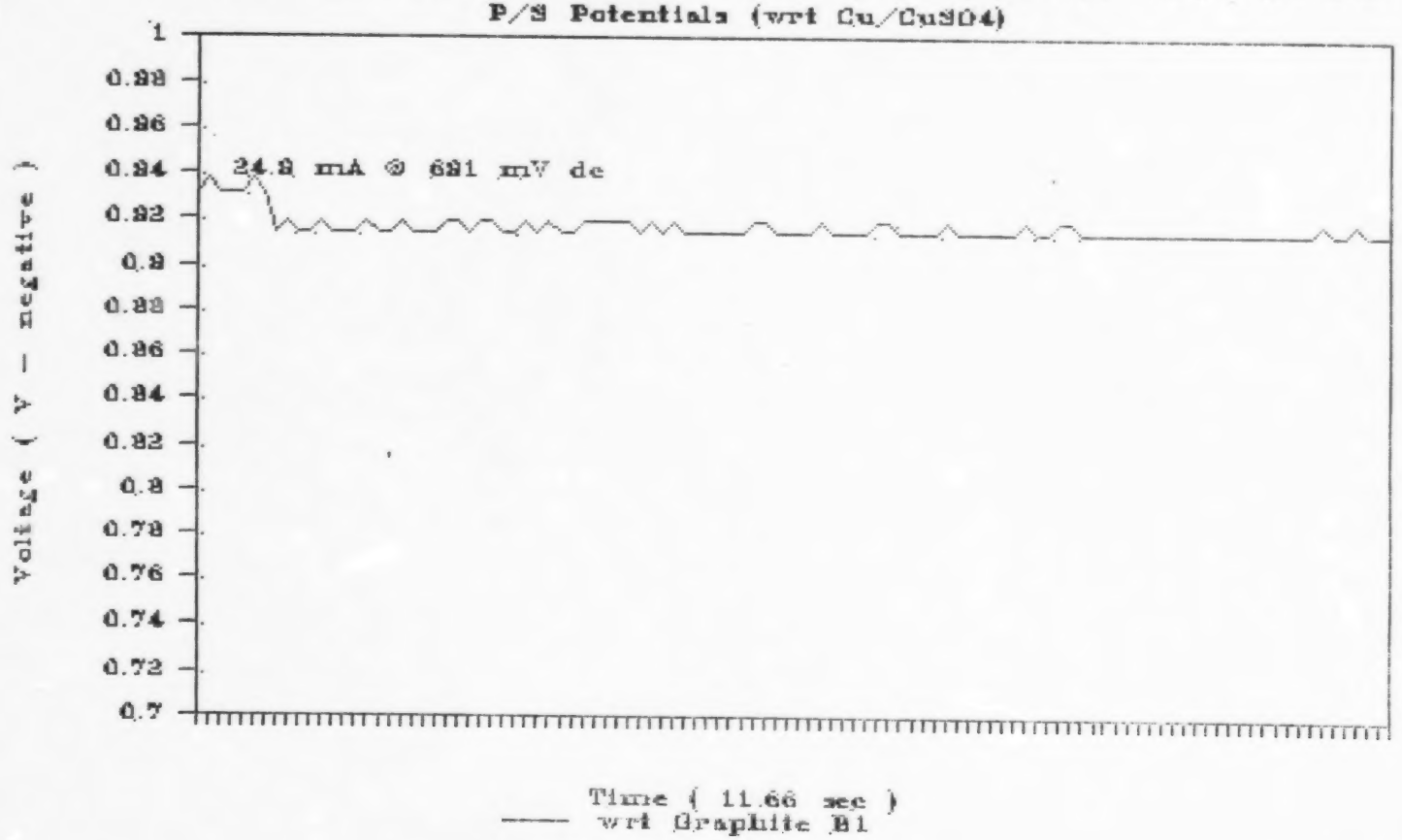
CANMET SPECIMEN # 1; FEB. 27, 1990



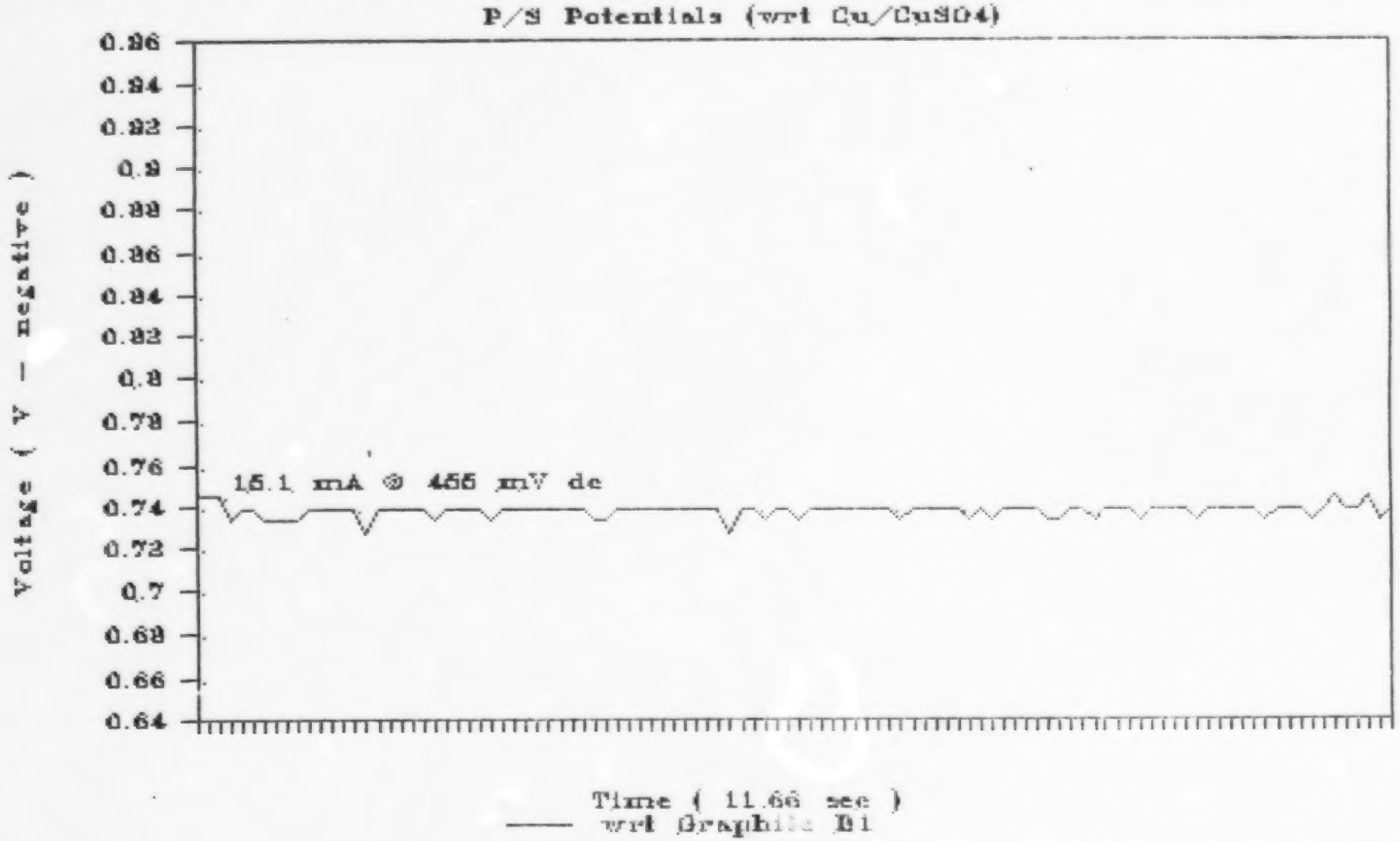
CANMET SPECIMEN # 1; FEB. 28, 1990



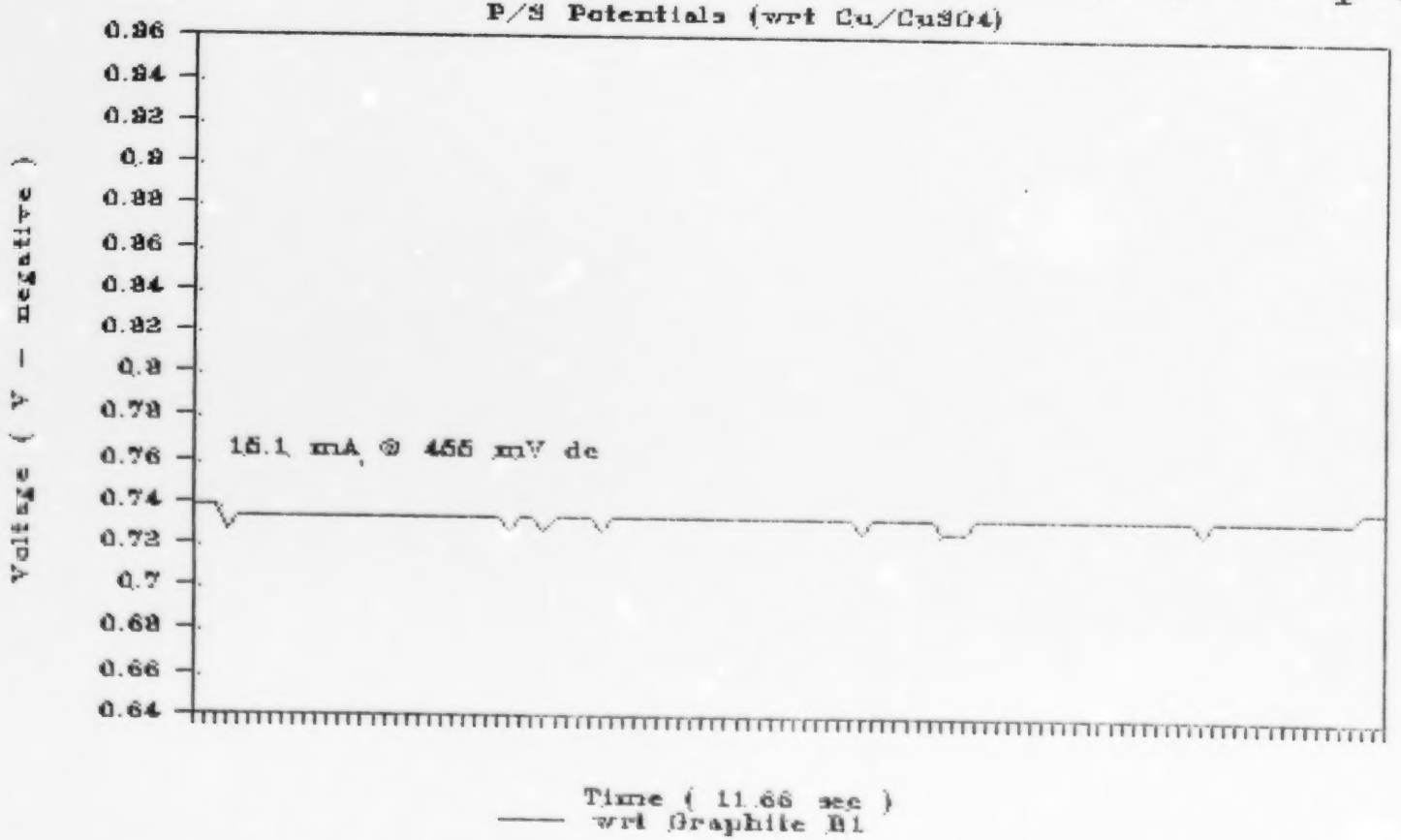
CANMET SPECIMEN # 1; MARCH 1, 1990



CANMET SPECIMEN # 1; MARCH 2, 1990 a.m.

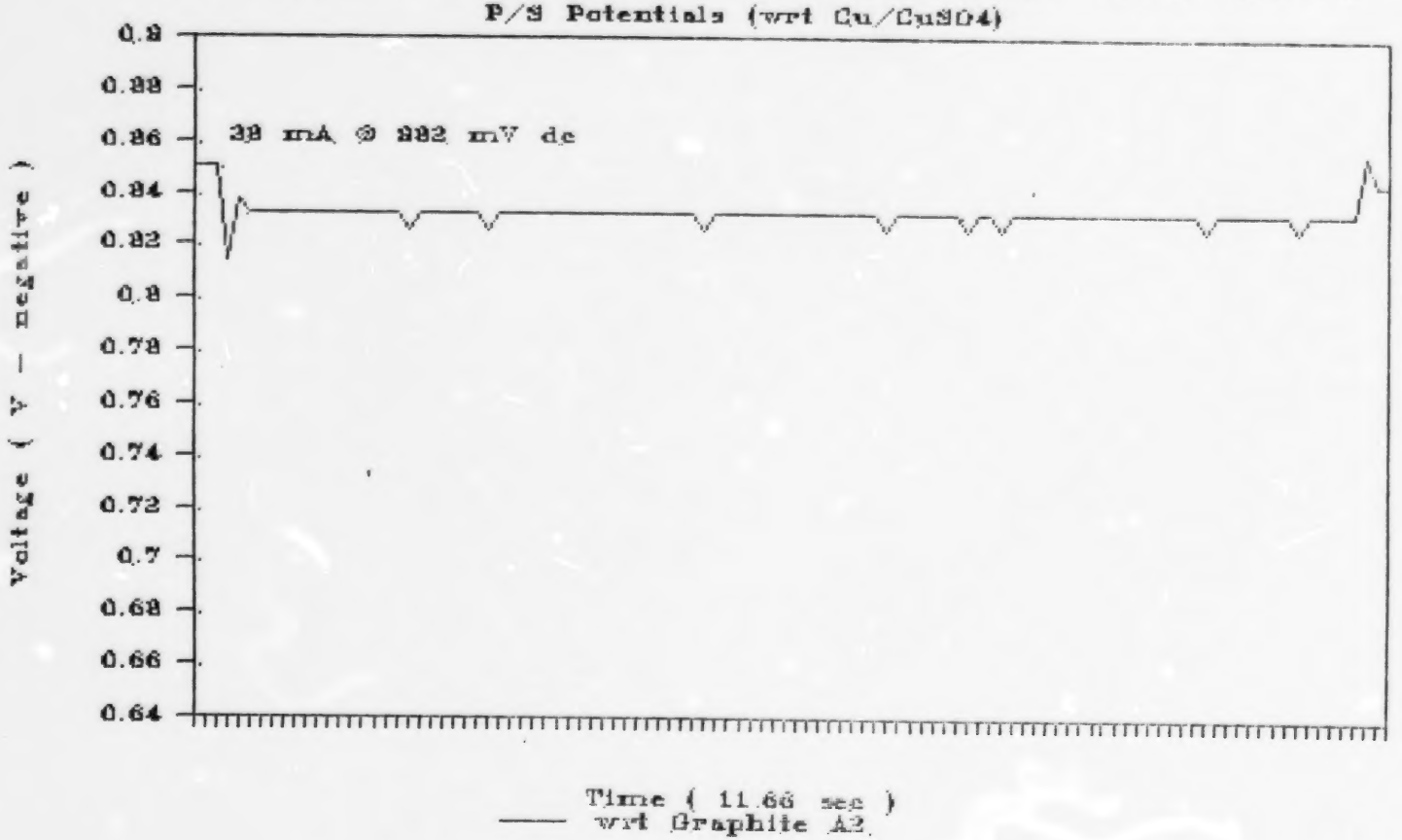


CANMET SPECIMEN # 1; MARCH 2, 1990 p.m.

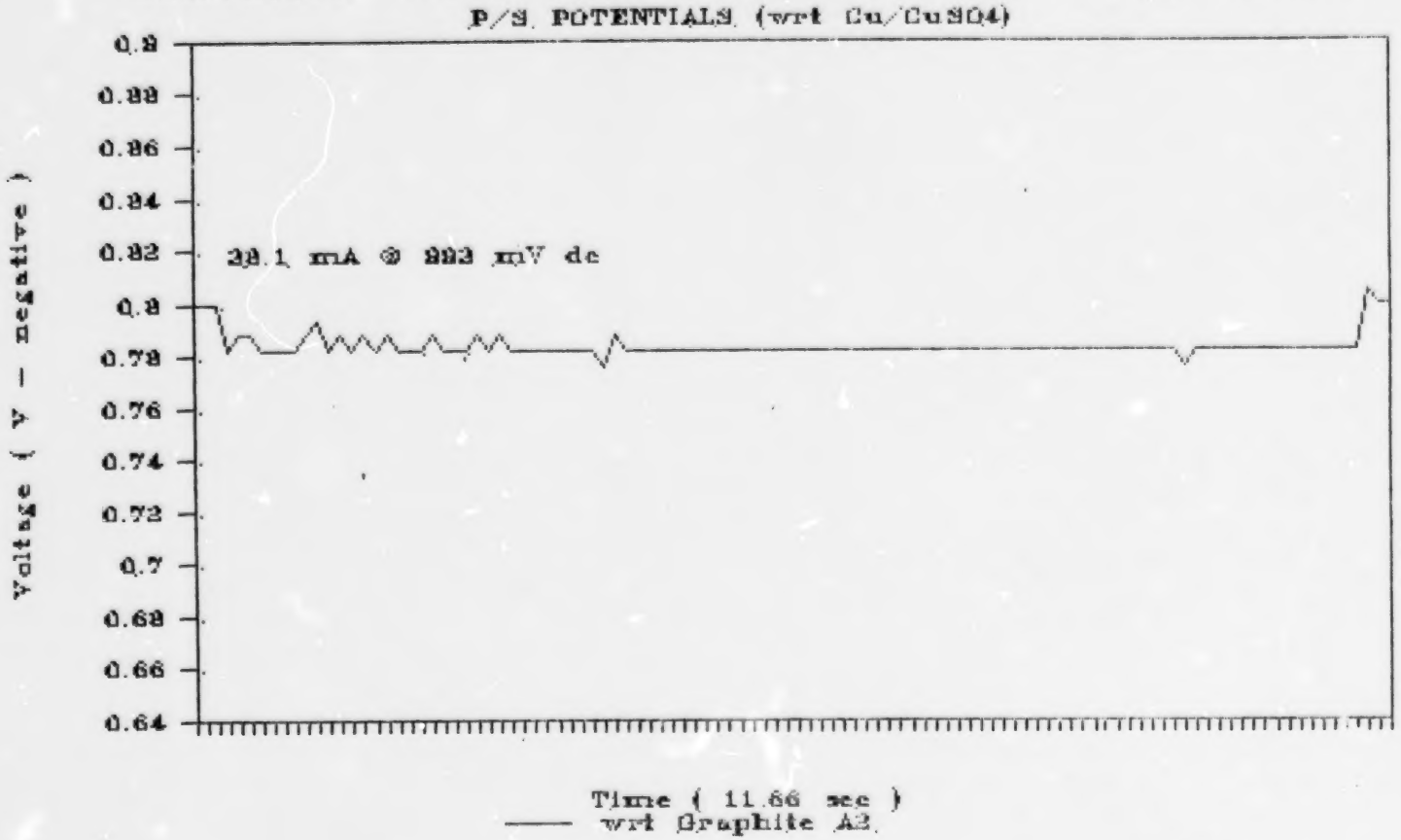


"Depolarization Curves - Graphite Reference A2"

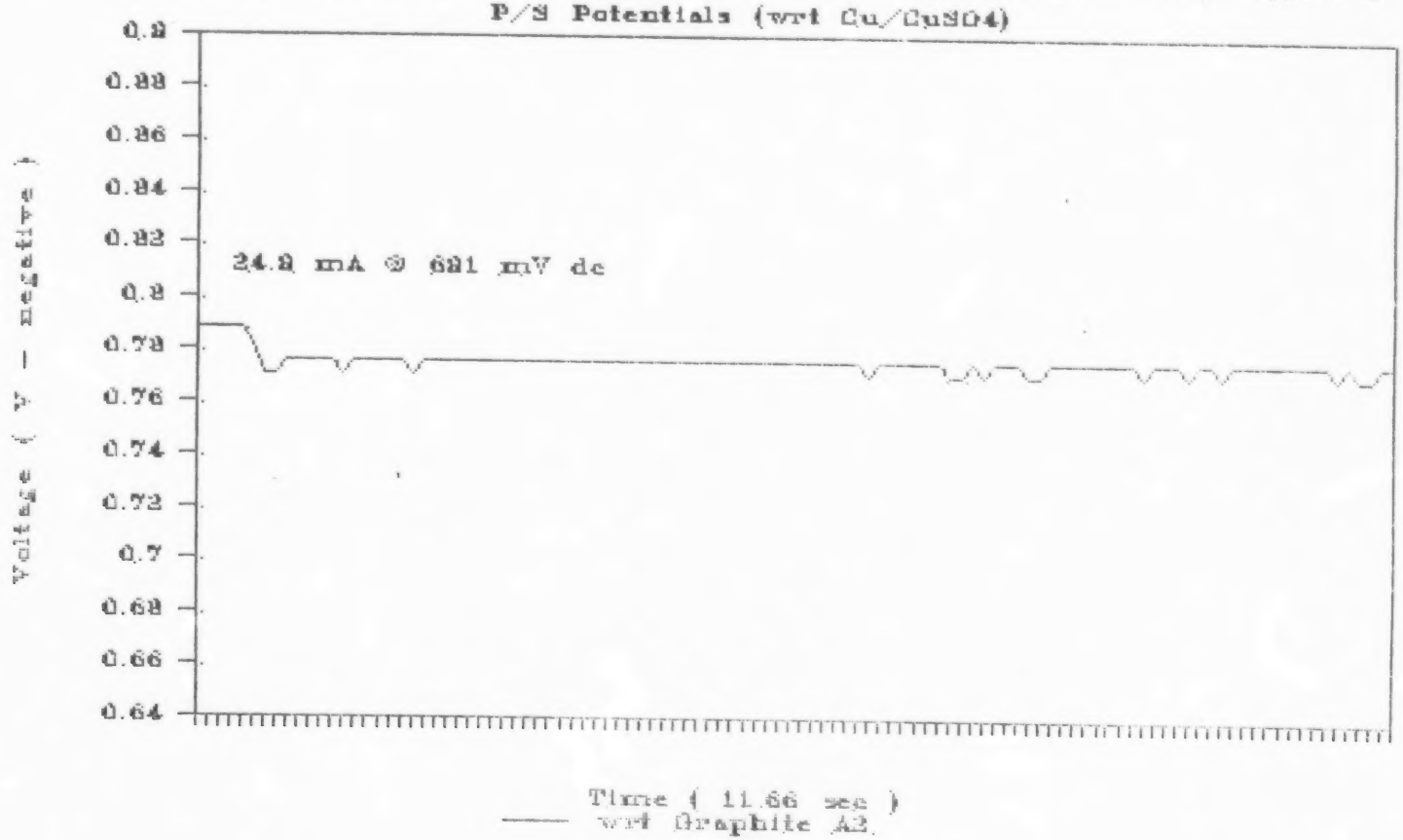
CANMET SPECIMEN # 1; FEB. 27, 1990



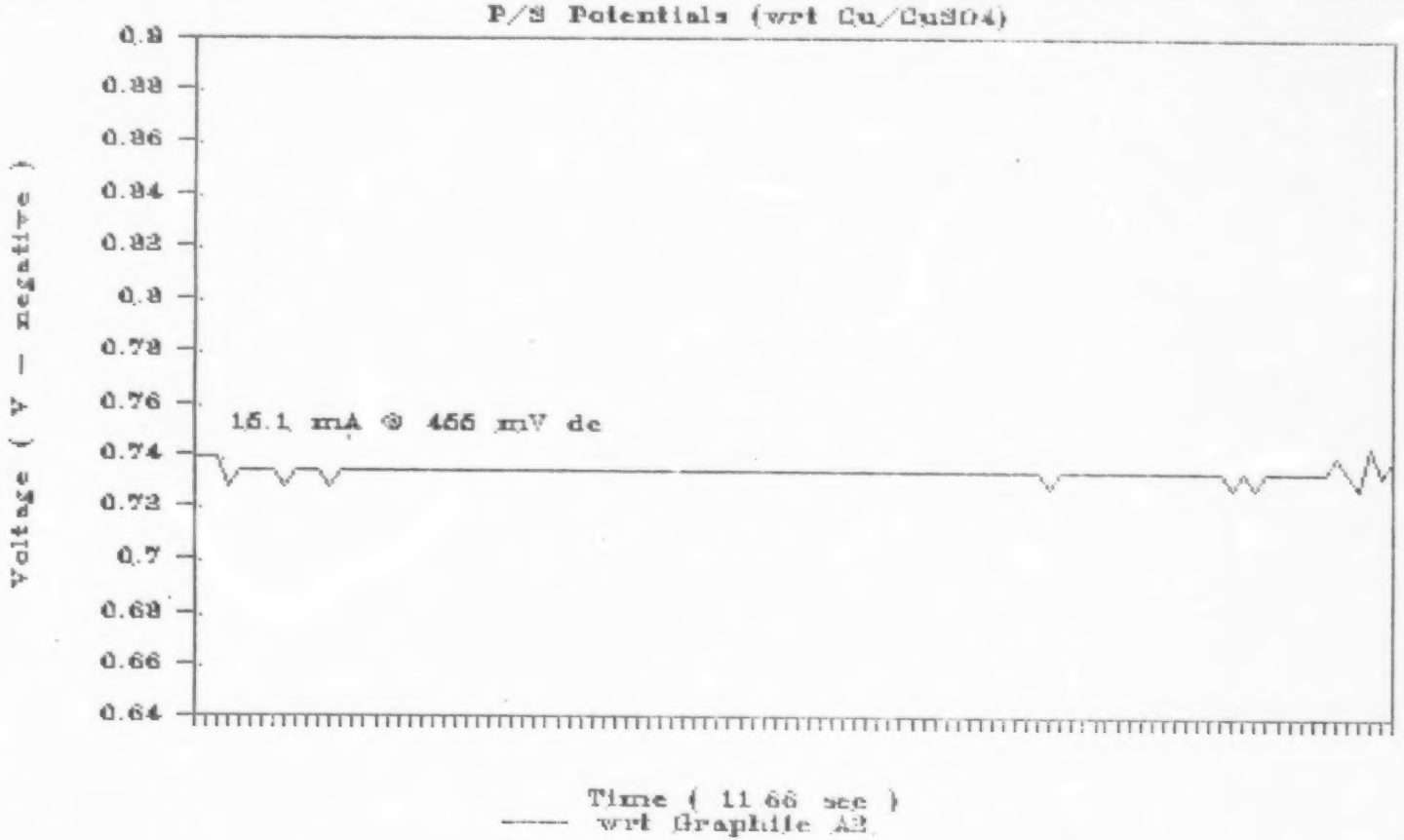
CANMET SPECIMEN # 1; FEB. 28, 1990



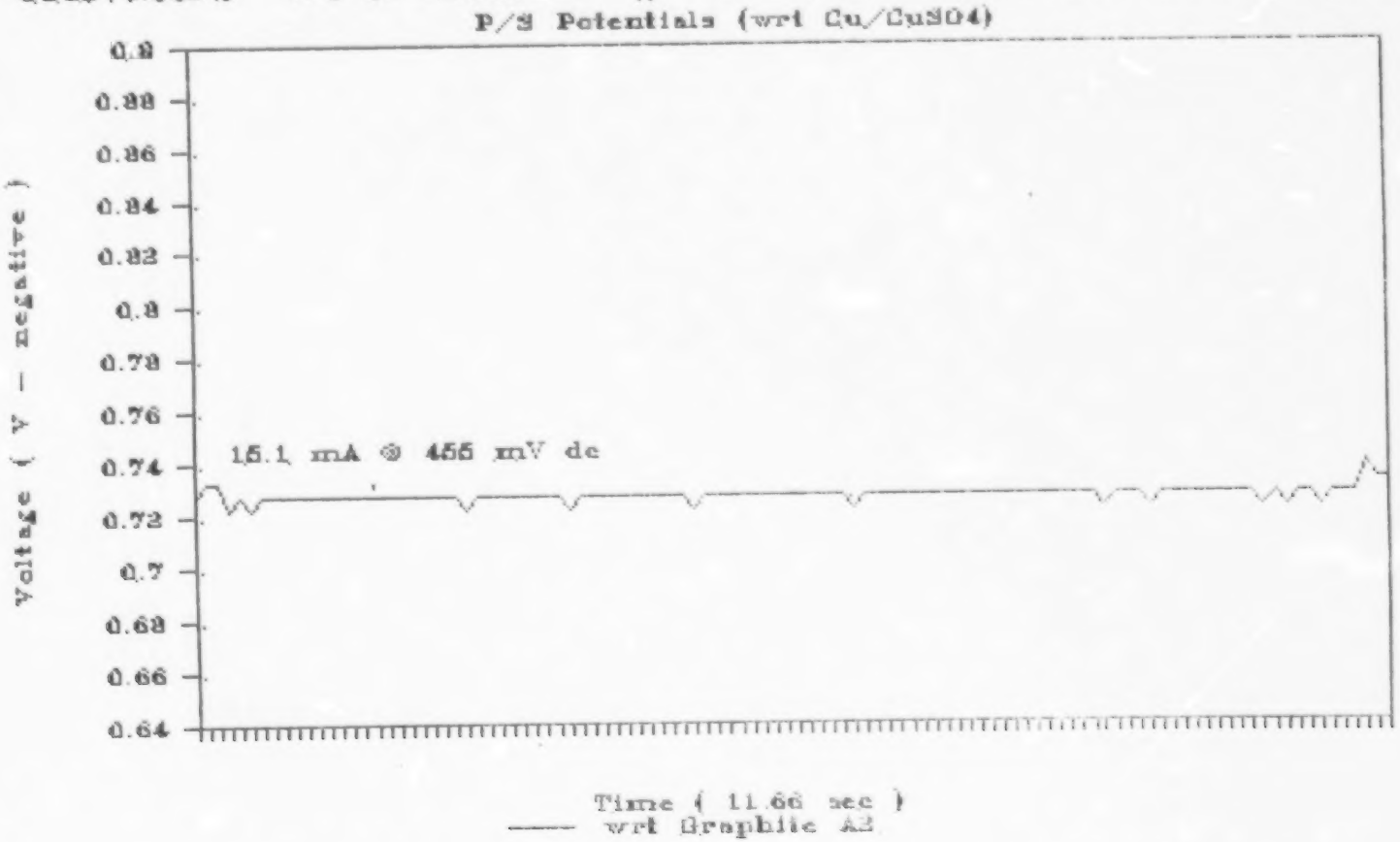
CANMET SPECIMEN # 1; MARCH 1, 1990



CANMET SPECIMEN # 1; MARCH 2, 1990 a.m.



CANMET SPECIMEN # 1; MARCH 2, 1990 p.m.



"Depolarization Curves - Graphite Reference A3"

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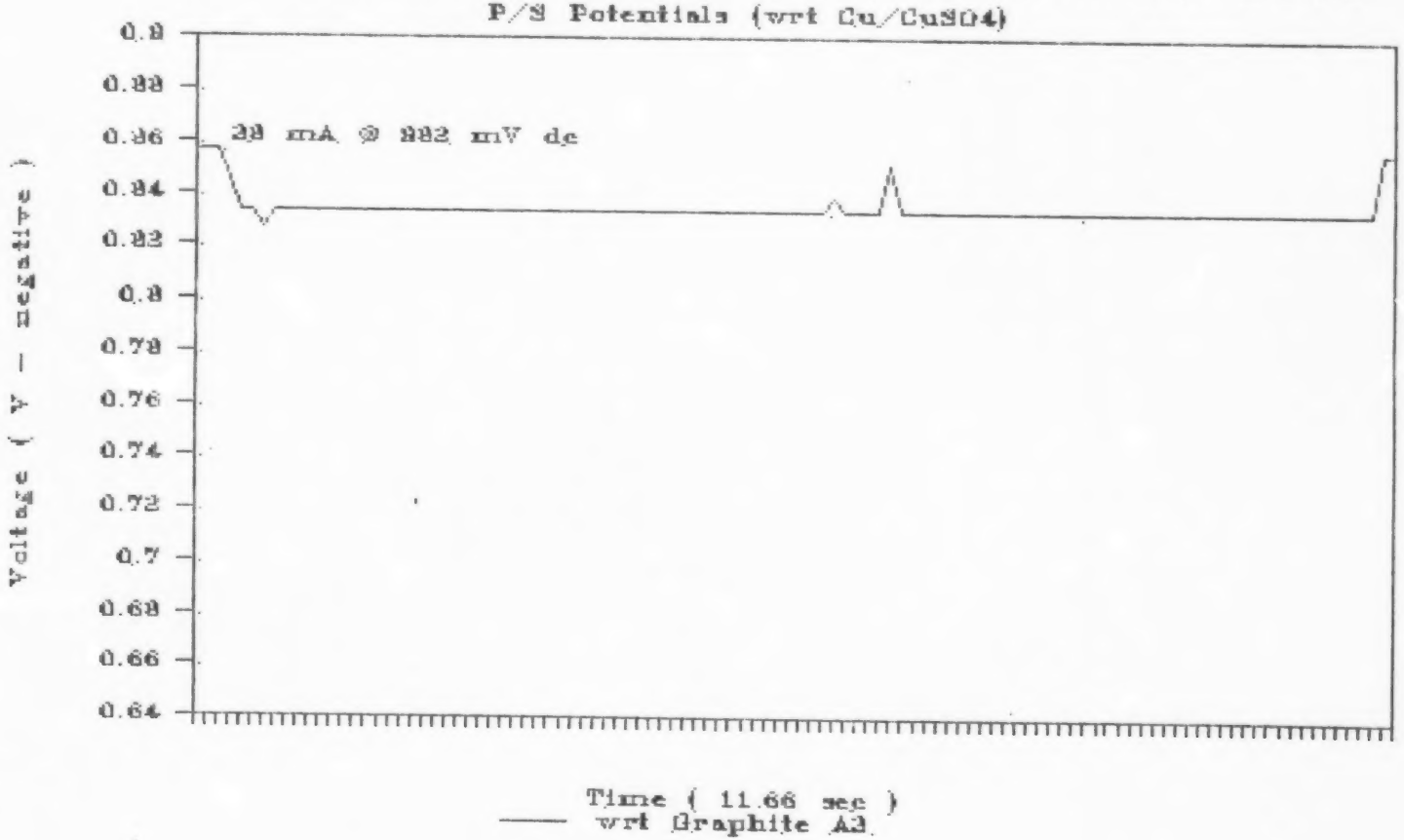

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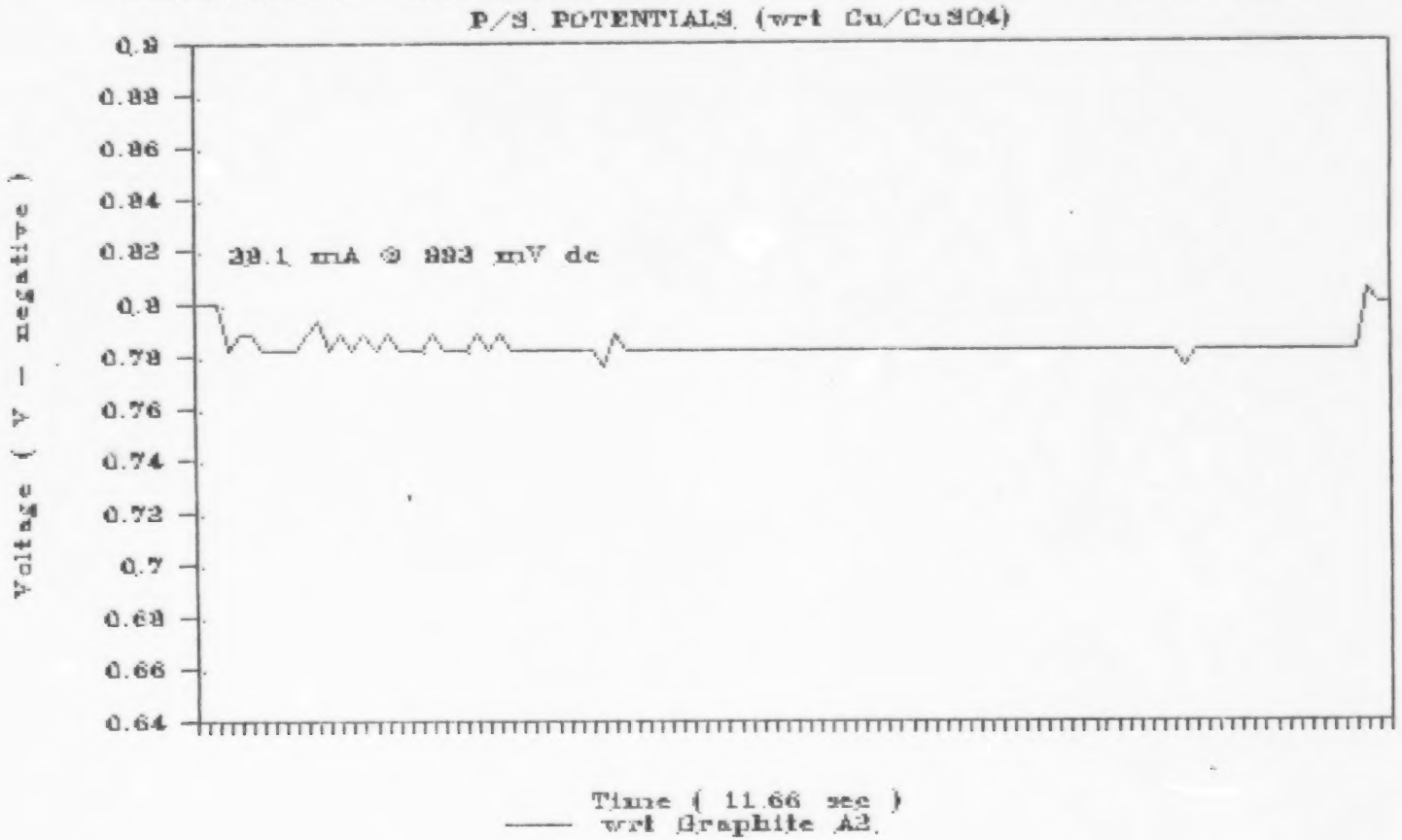

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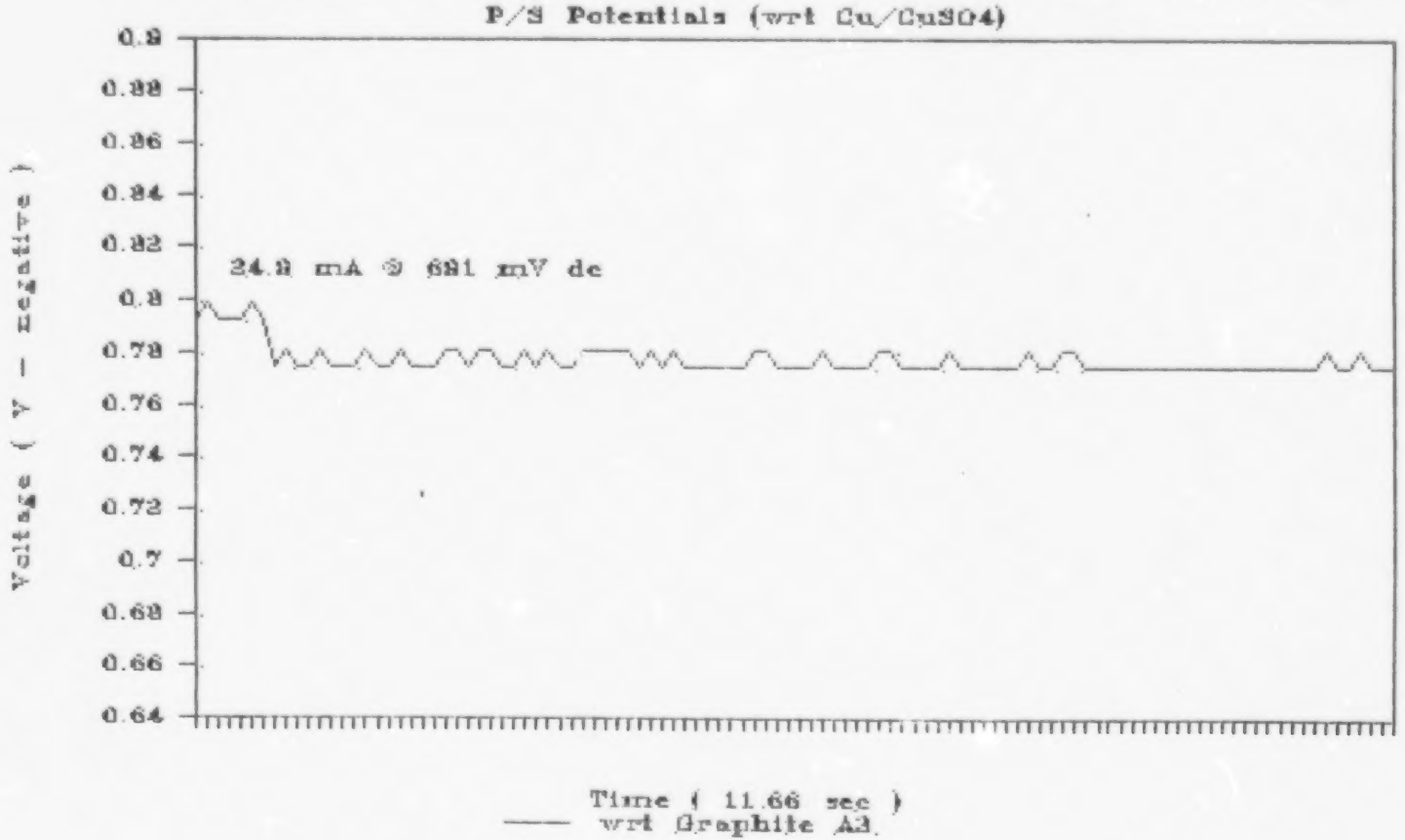

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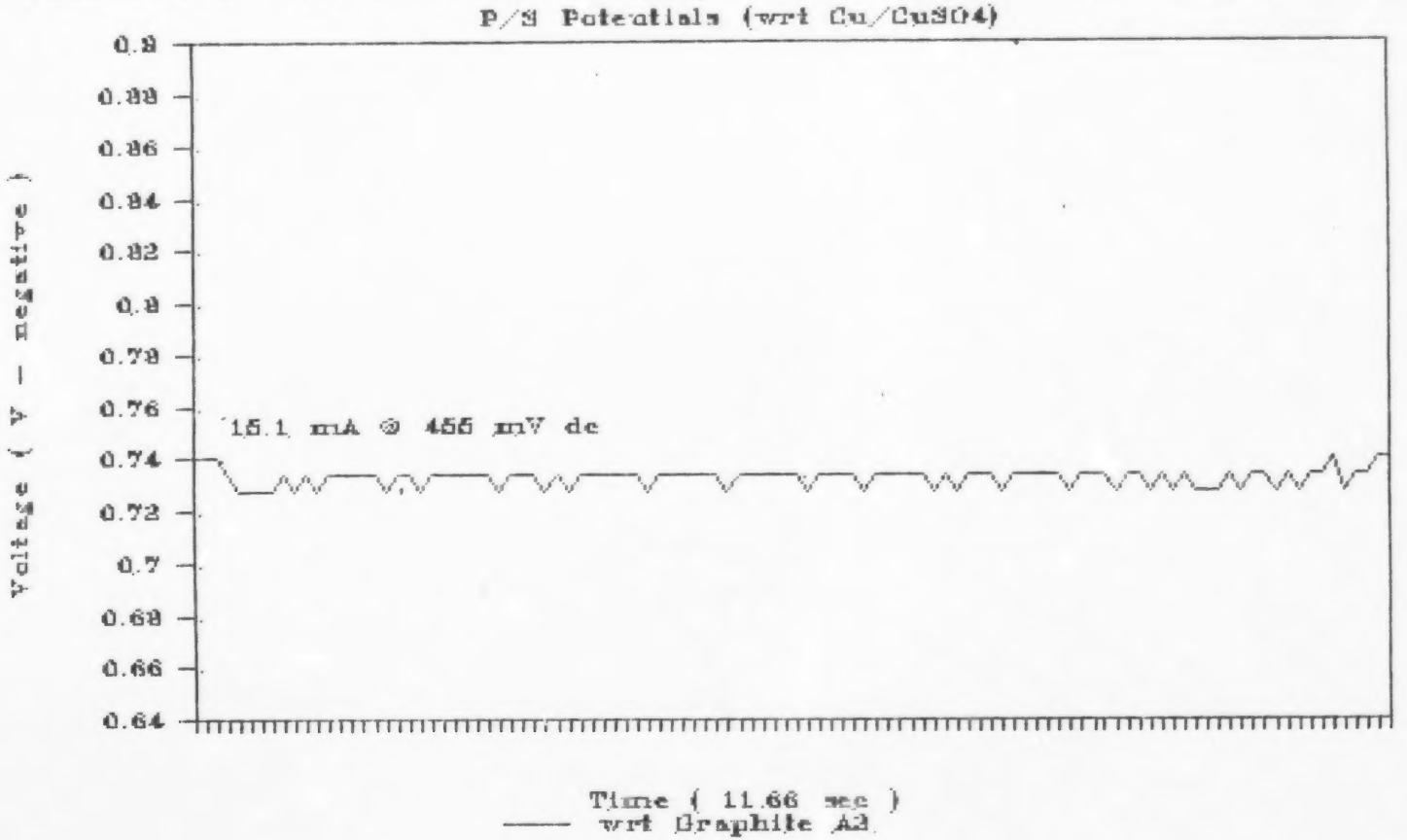
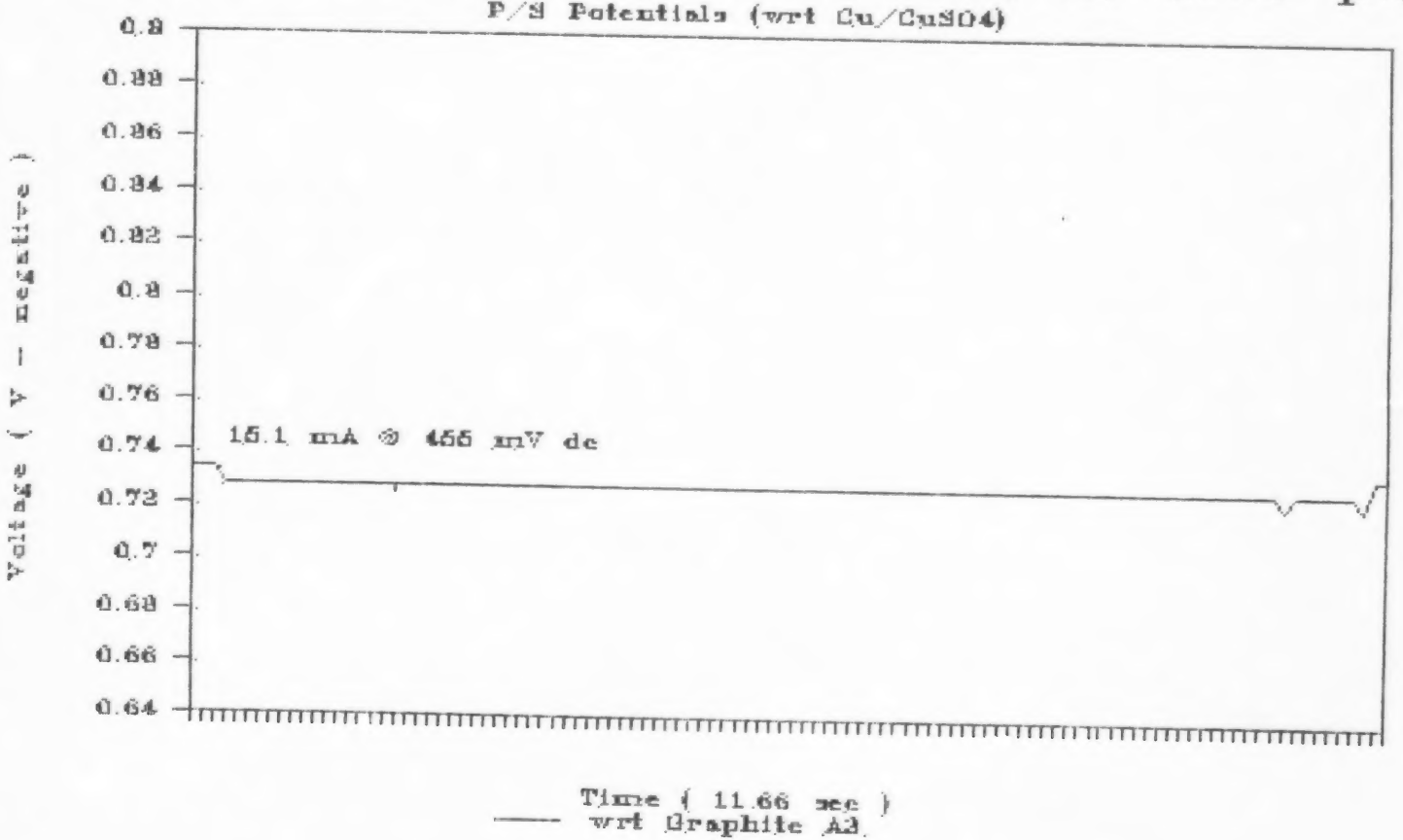
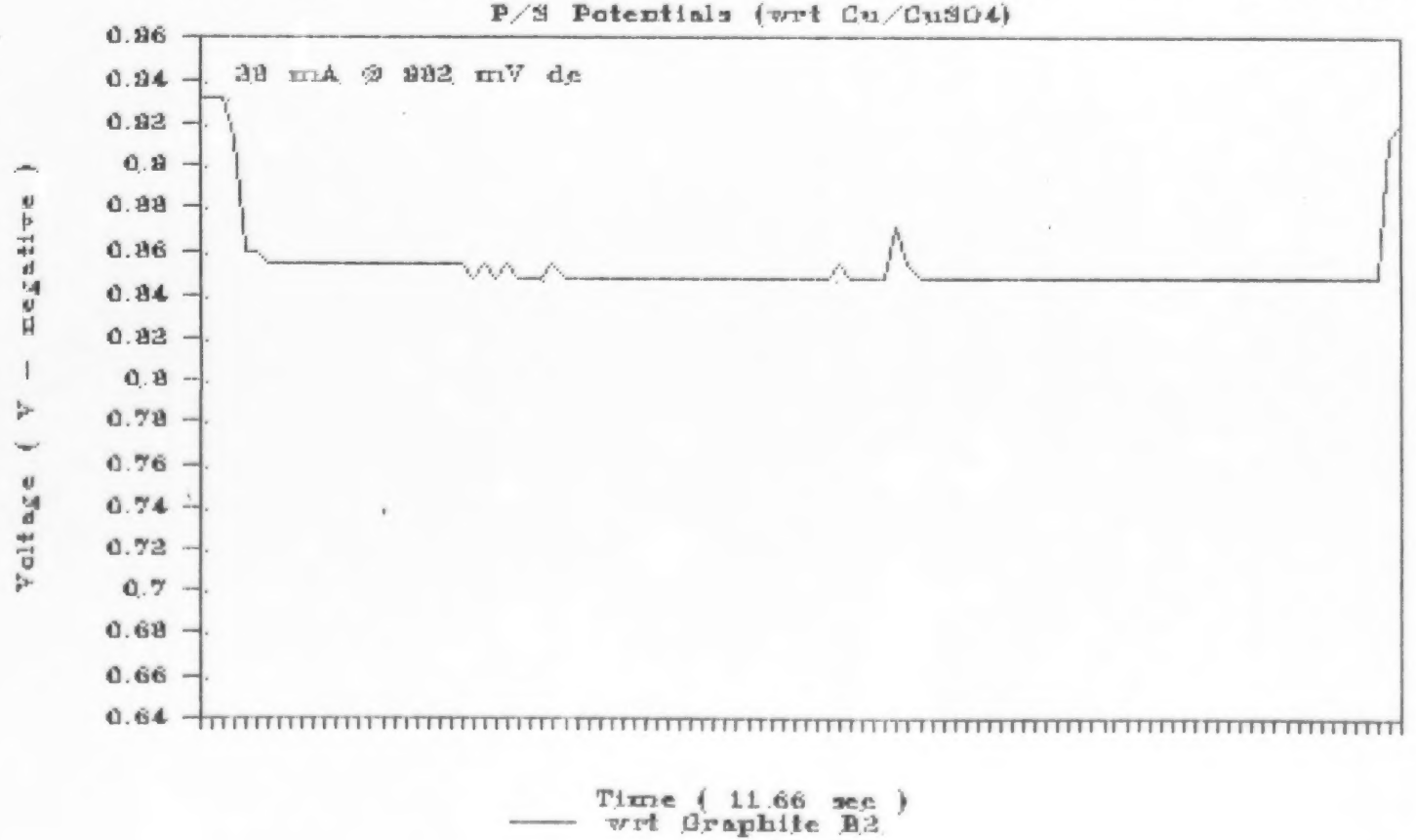


CANMET SPECIMEN # 1; MARCH 2, 1990 p.m.

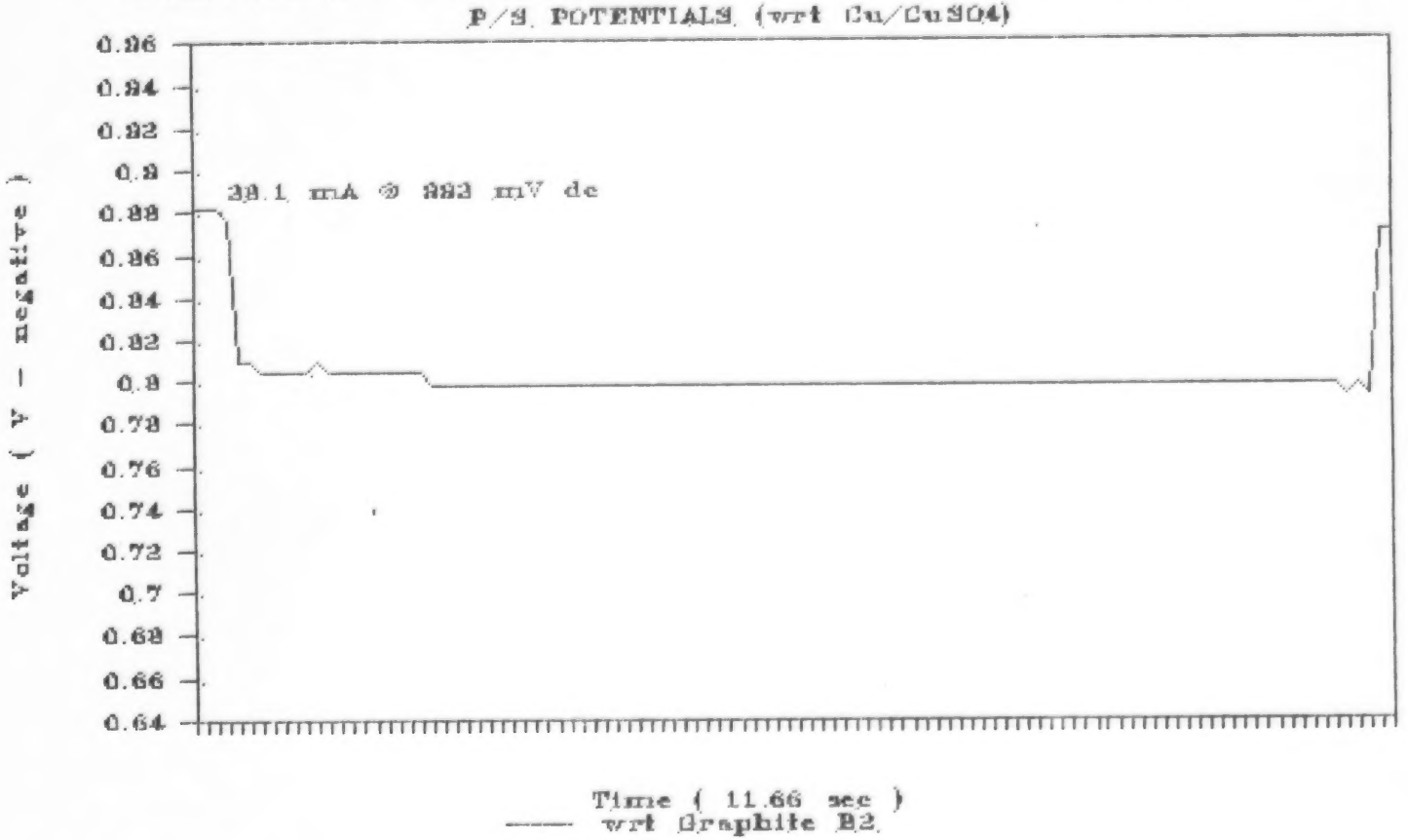


"Depolarization Curves - Graphite Reference B2"

CANMET SPECIMEN # 1; FEB. 27, 1990



CANMET SPECIMEN # 1; FEB. 28, 1990



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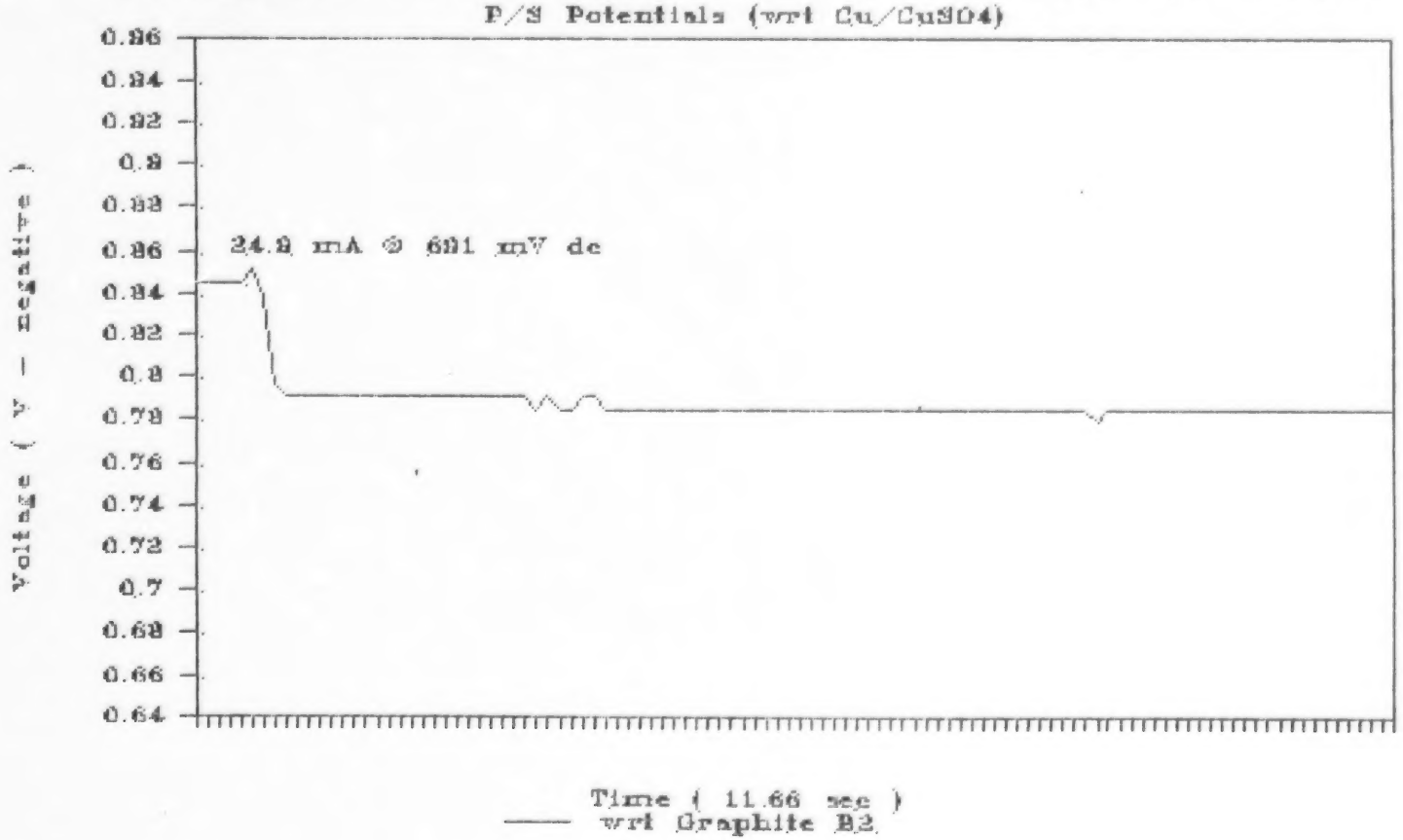
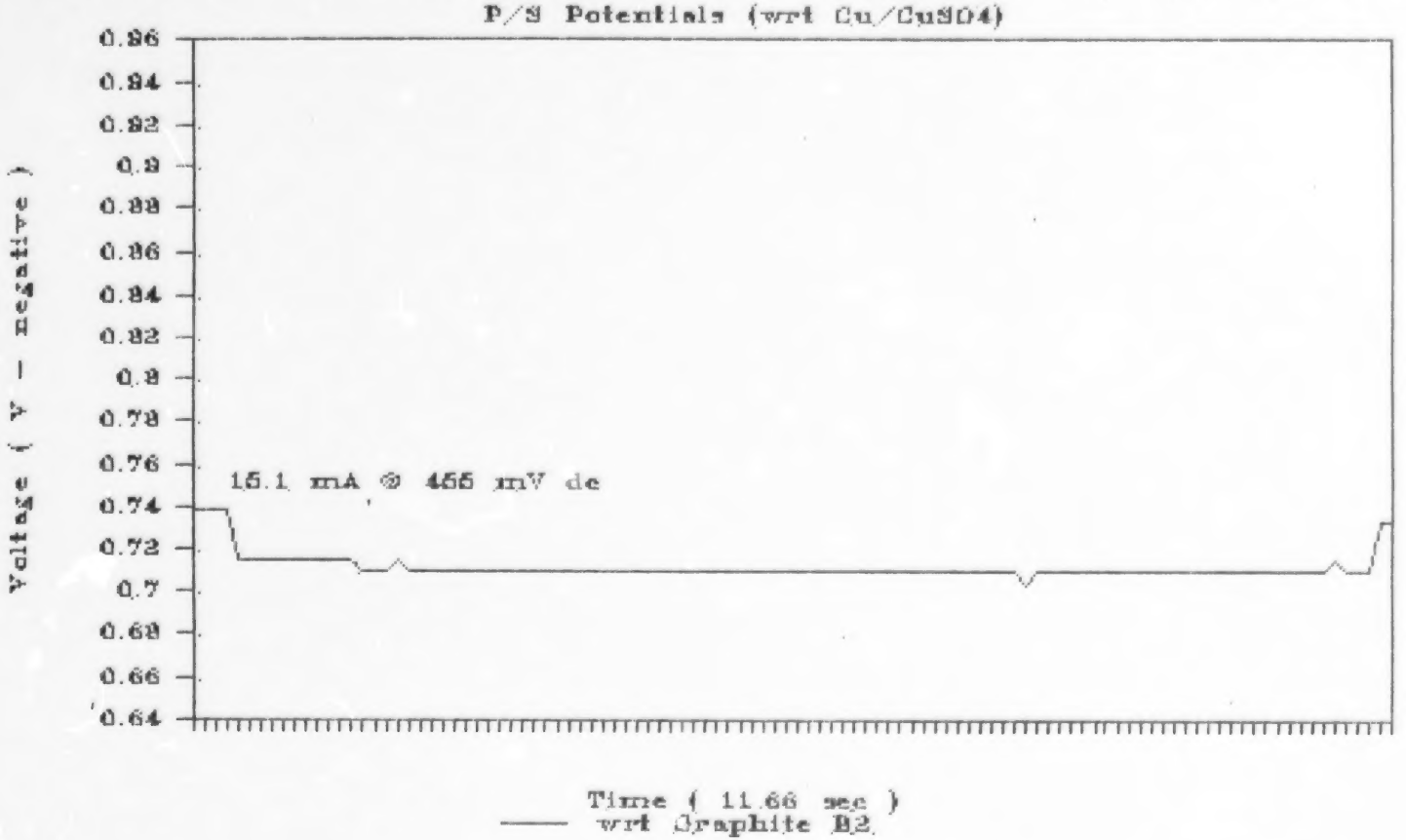
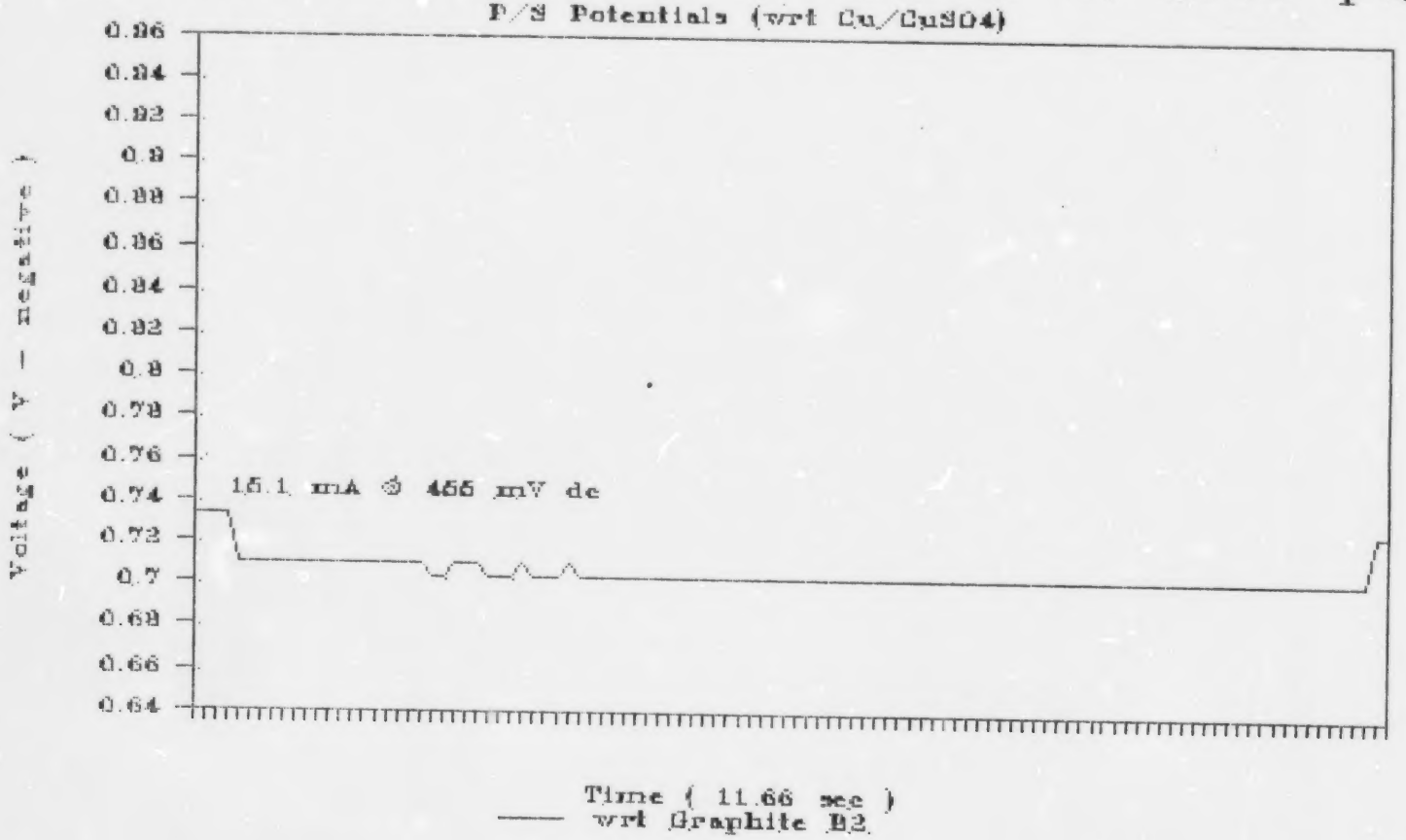


CANMET SPECIMEN # 1; MARCH 2, 1990 a.m.

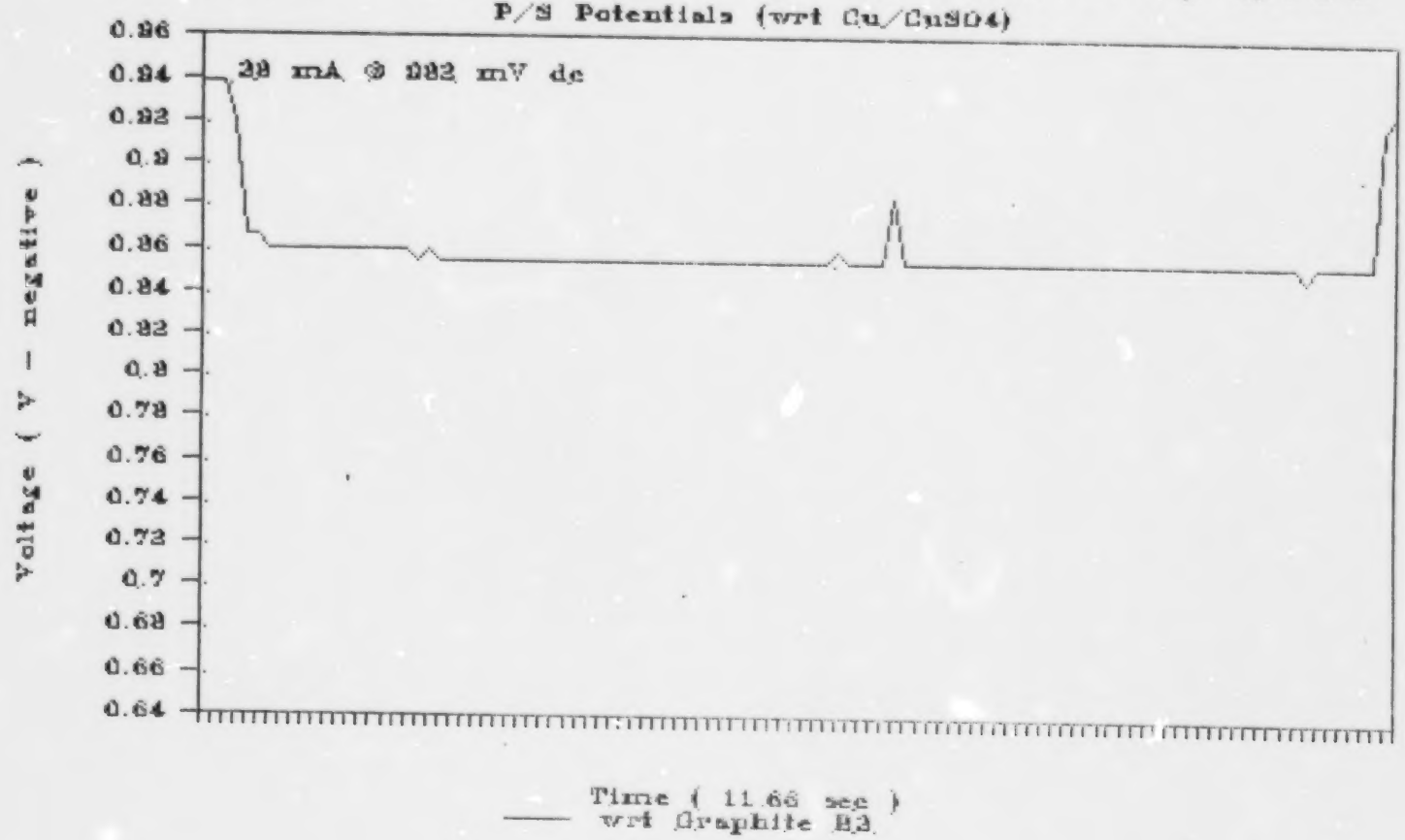


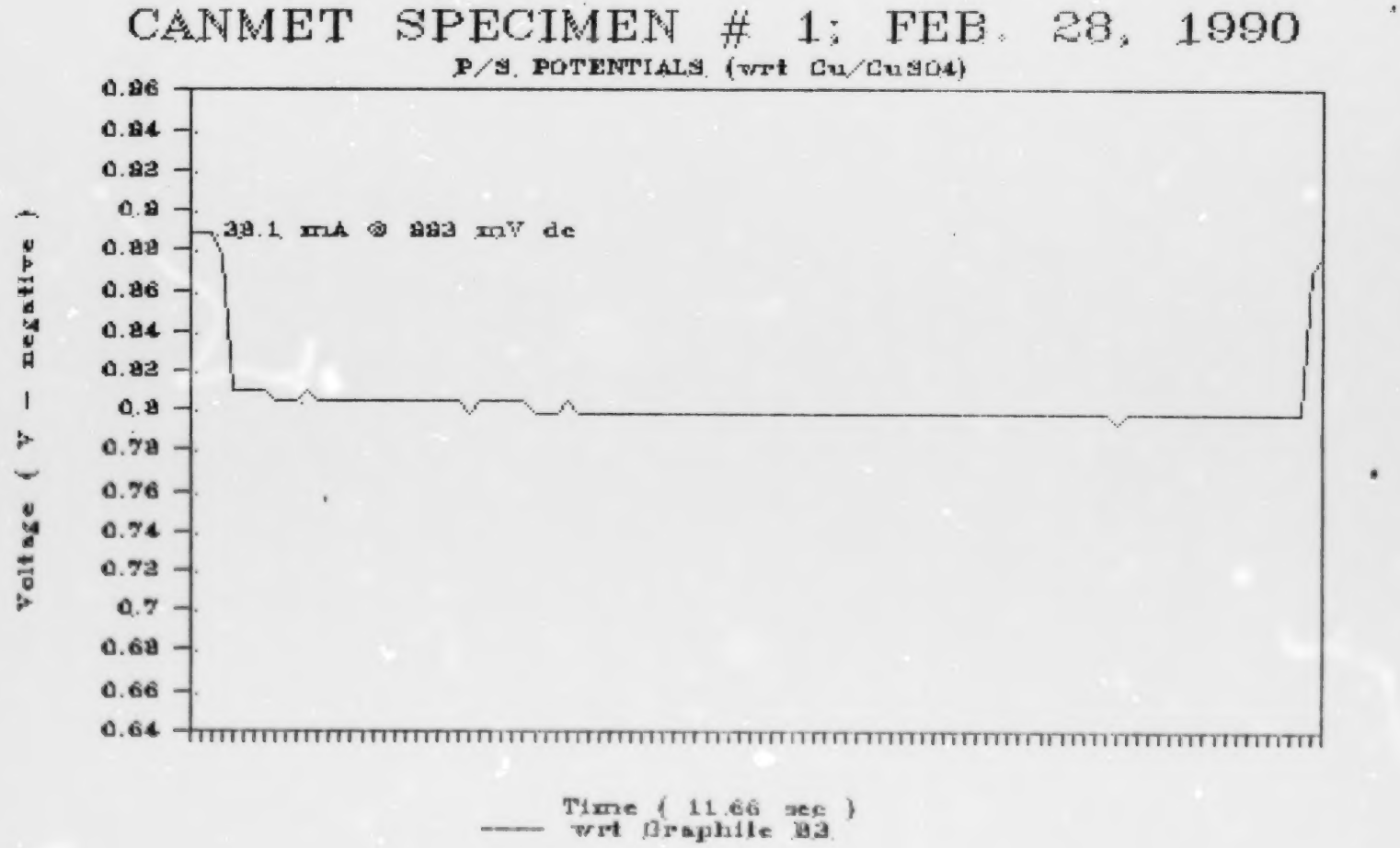
CANMET SPECIMEN # 1; MARCH 2, 1990 p.m.



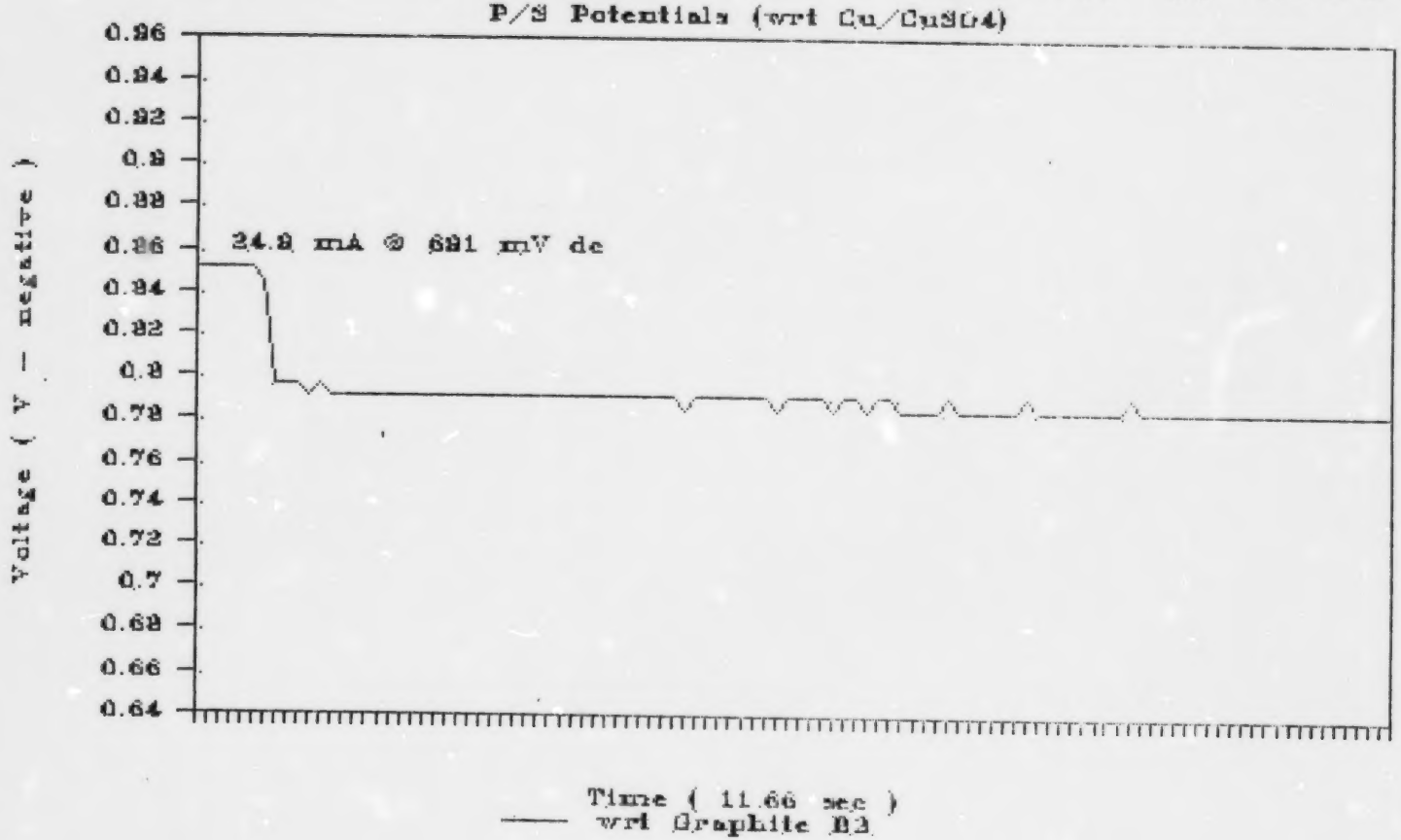
"Depolarization Curves - Graphite Reference B3"

CANMET SPECIMEN # 1; FEB. 27, 1990

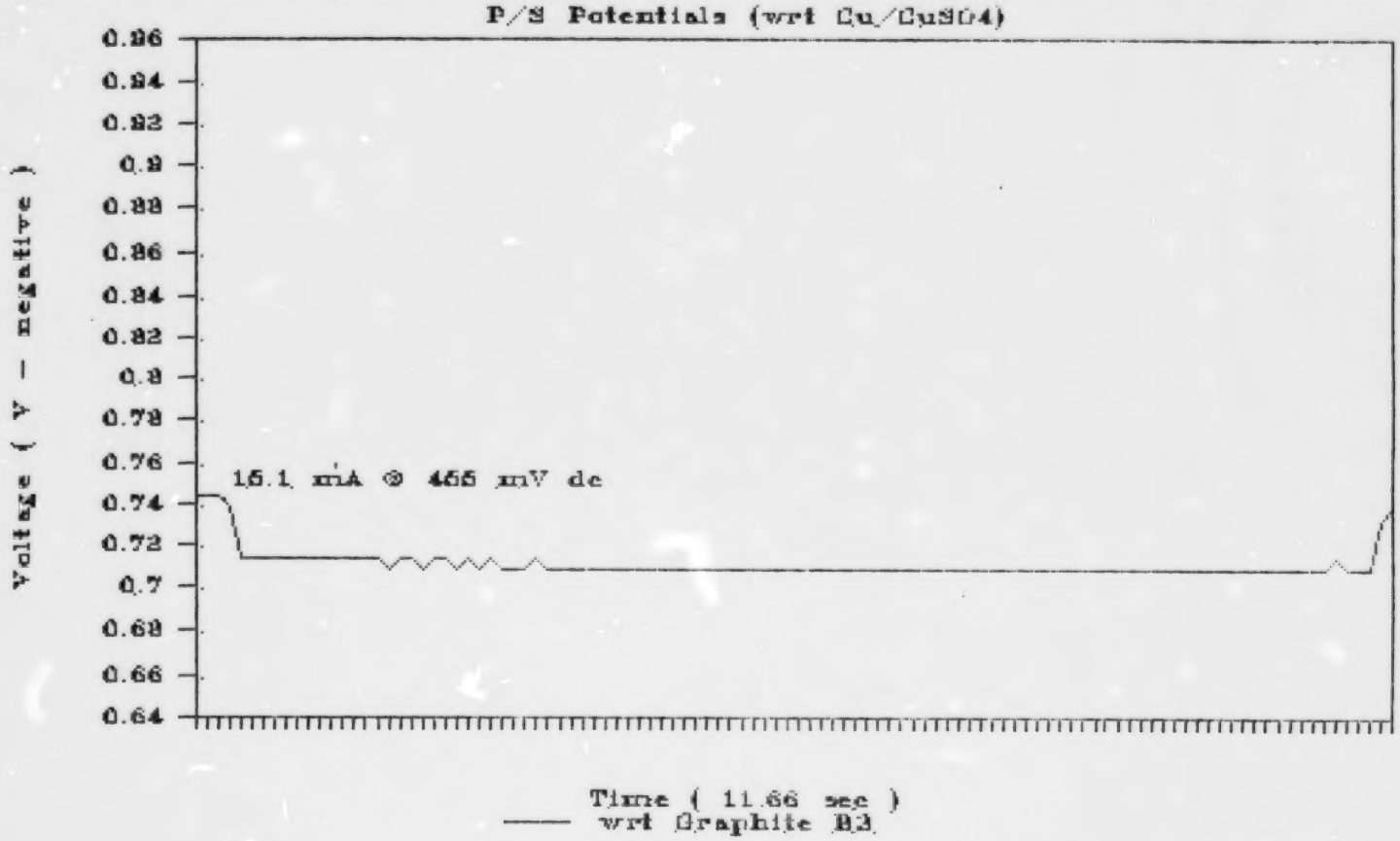



CANMET SPECIMEN # 1; FEB. 28, 1990
P/S. POTENTIALS (vrt Cu/CuSO4)
0.96
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
0.7
0.68
0.66
0.64
Voltage (V - negative)
39.1 mA @ 883 mV dc
Time (11.66 sec)
vrt Graphite E3

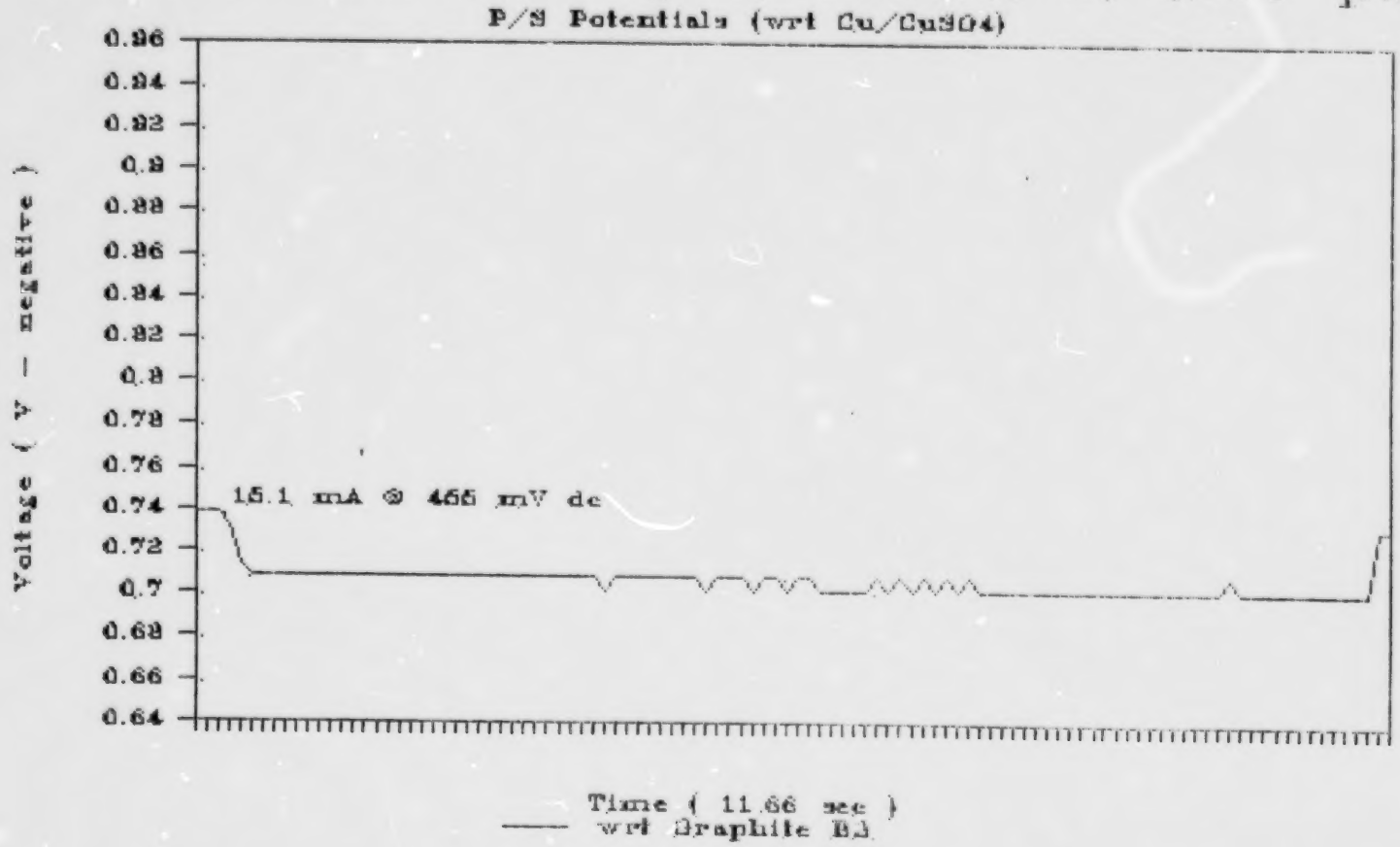
CANMET SPECIMEN # 1; MARCH 1, 1990



CANMET SPECIMEN # 1; MARCH 2, 1990 a.m.

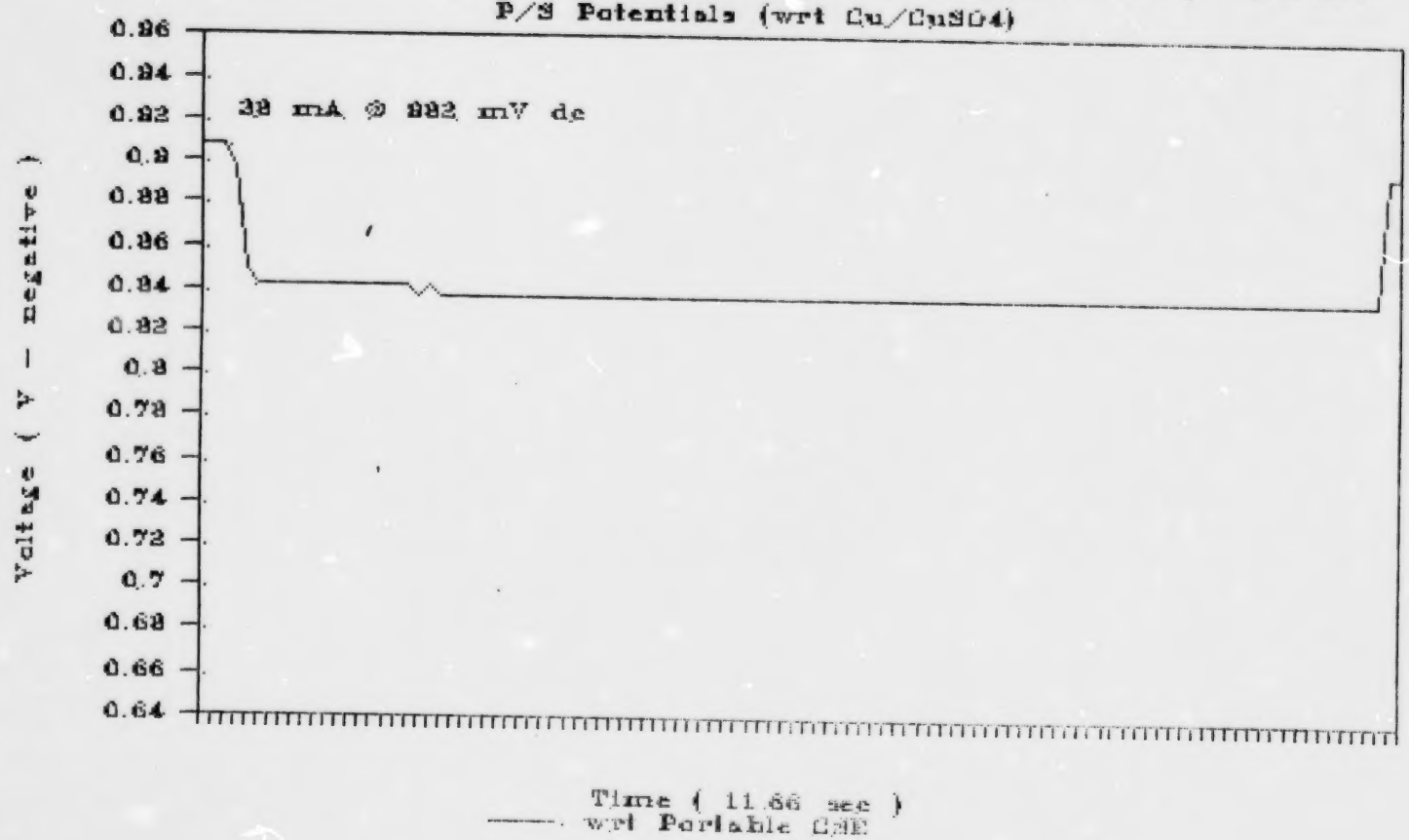


CANMET SPECIMEN # 1; MARCH 2, 1990 p.m.

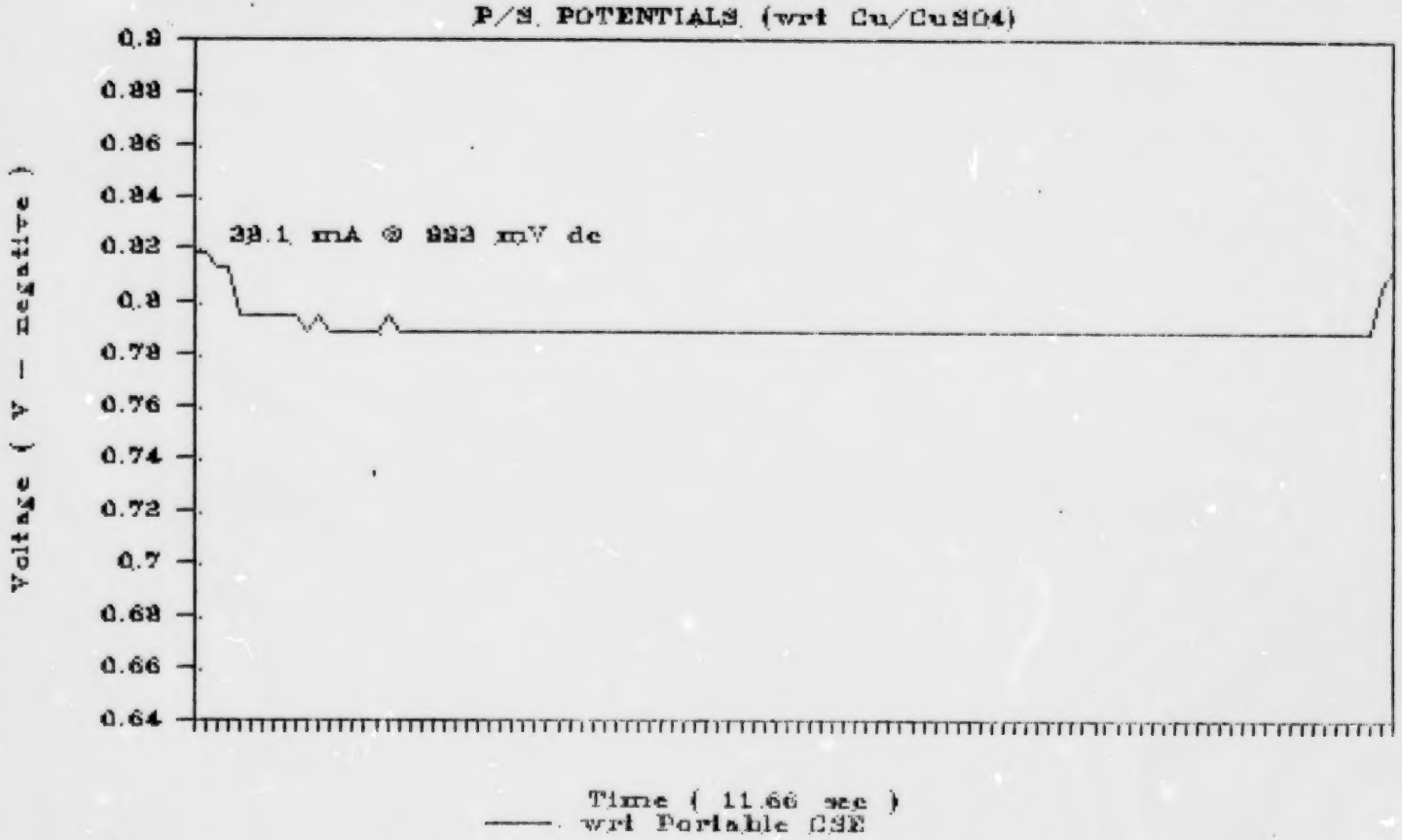


"Depolarization Curves: Portable CSE"

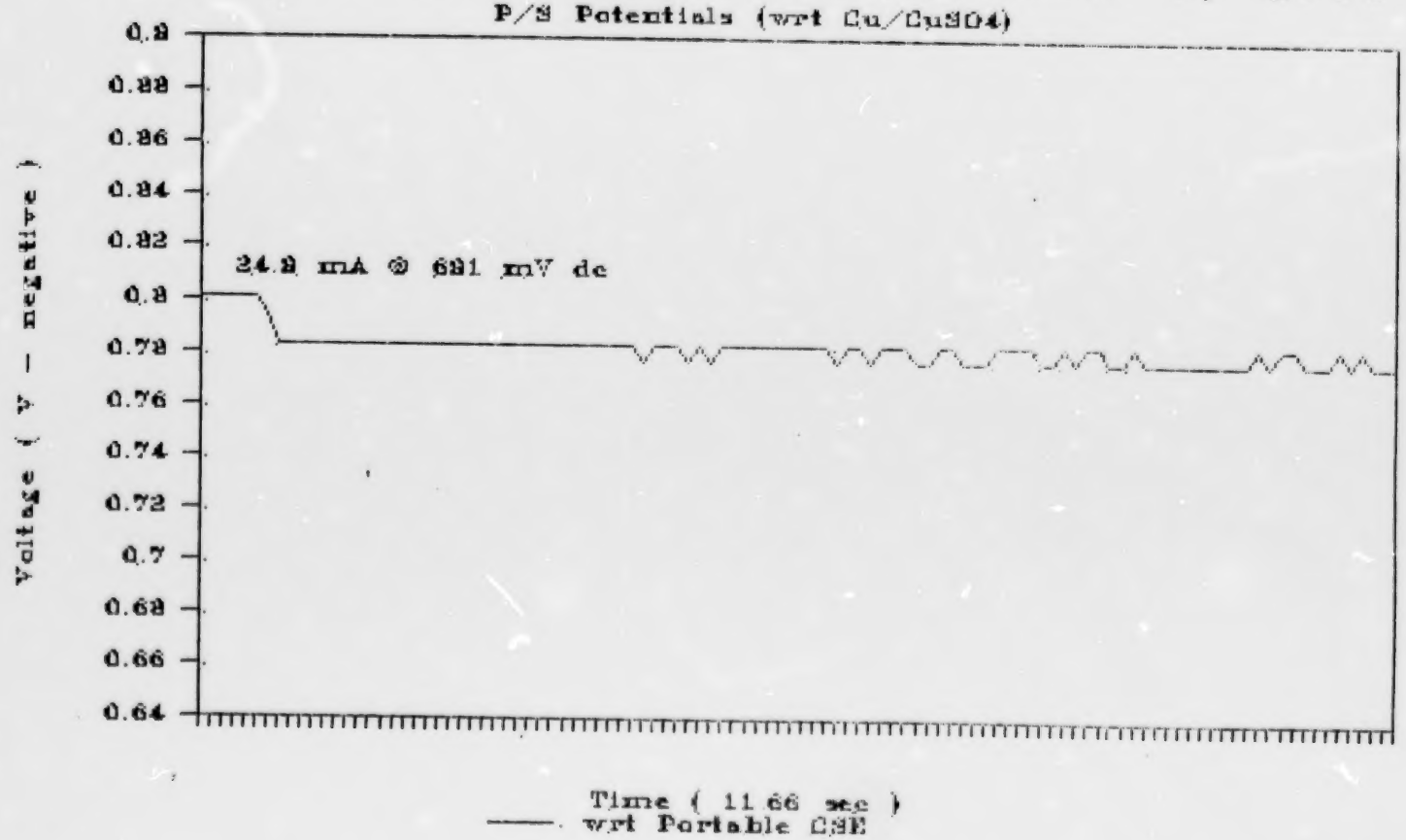
CANMET SPECIMEN # 1; FEB. 27, 1990



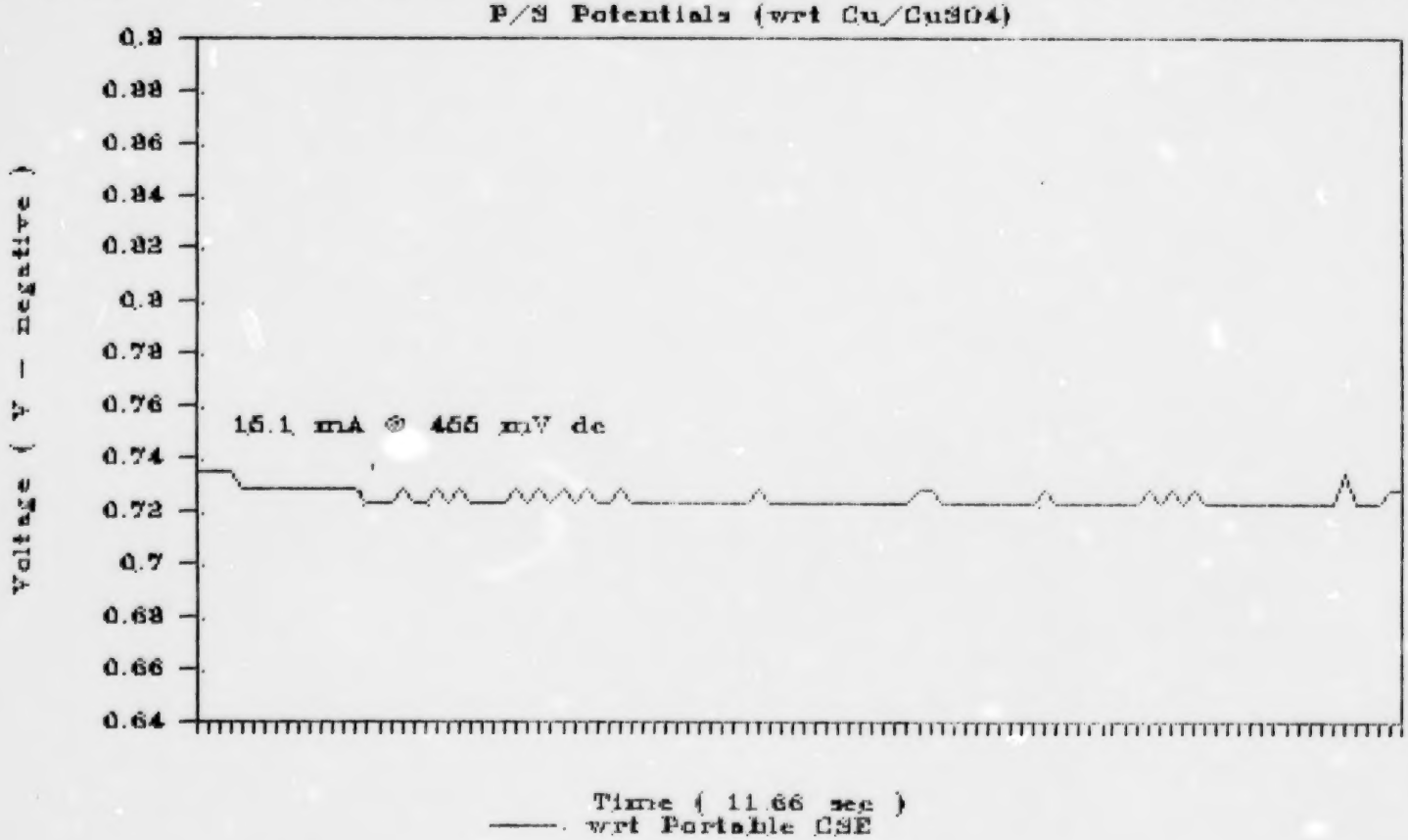
CANMET SPECIMEN # 1; FEB. 28, 1990



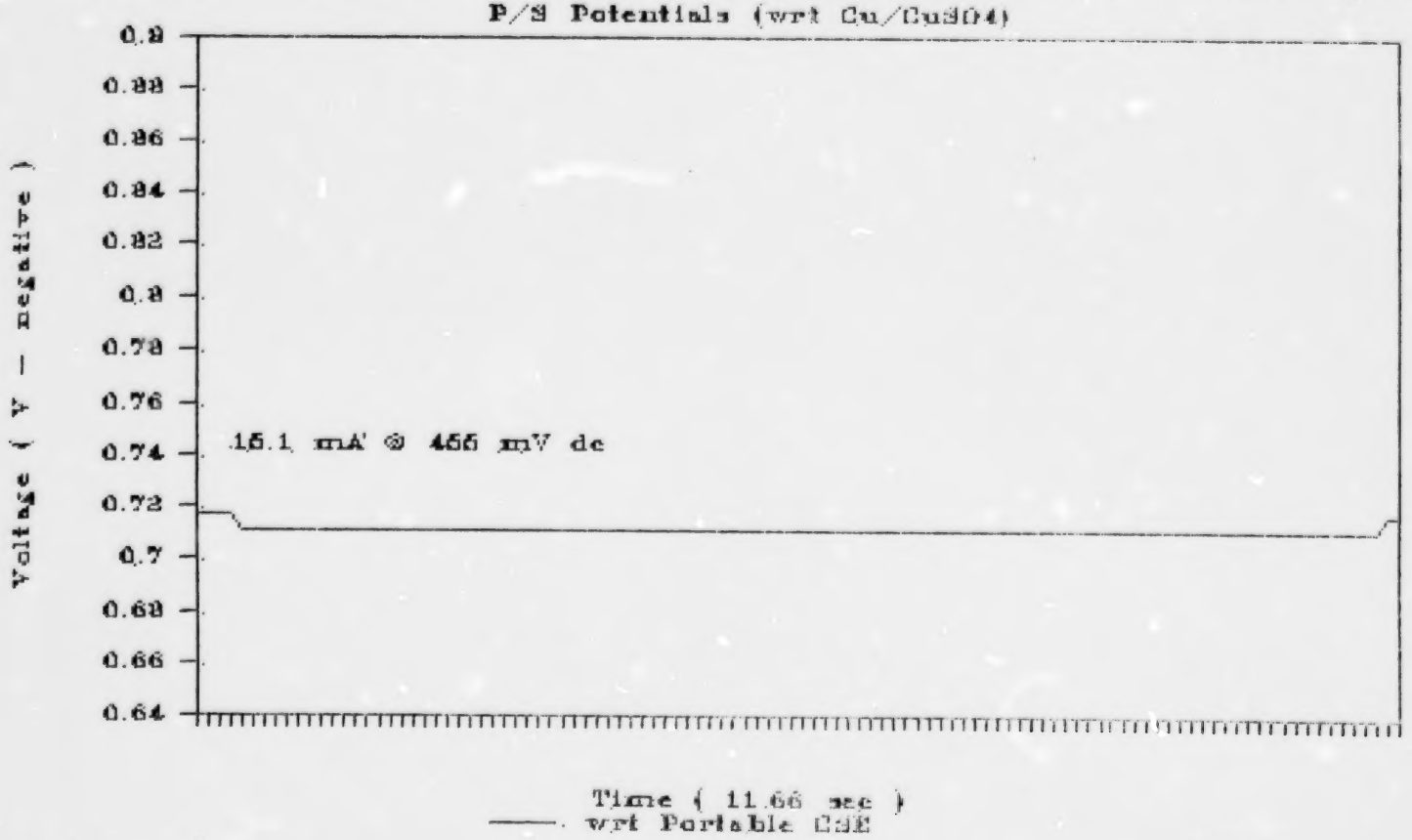
CANMET SPECIMEN # 1; MARCH 1, 1990



CANMET SPECIMEN # 1; MARCH 2, 1990 a.m.

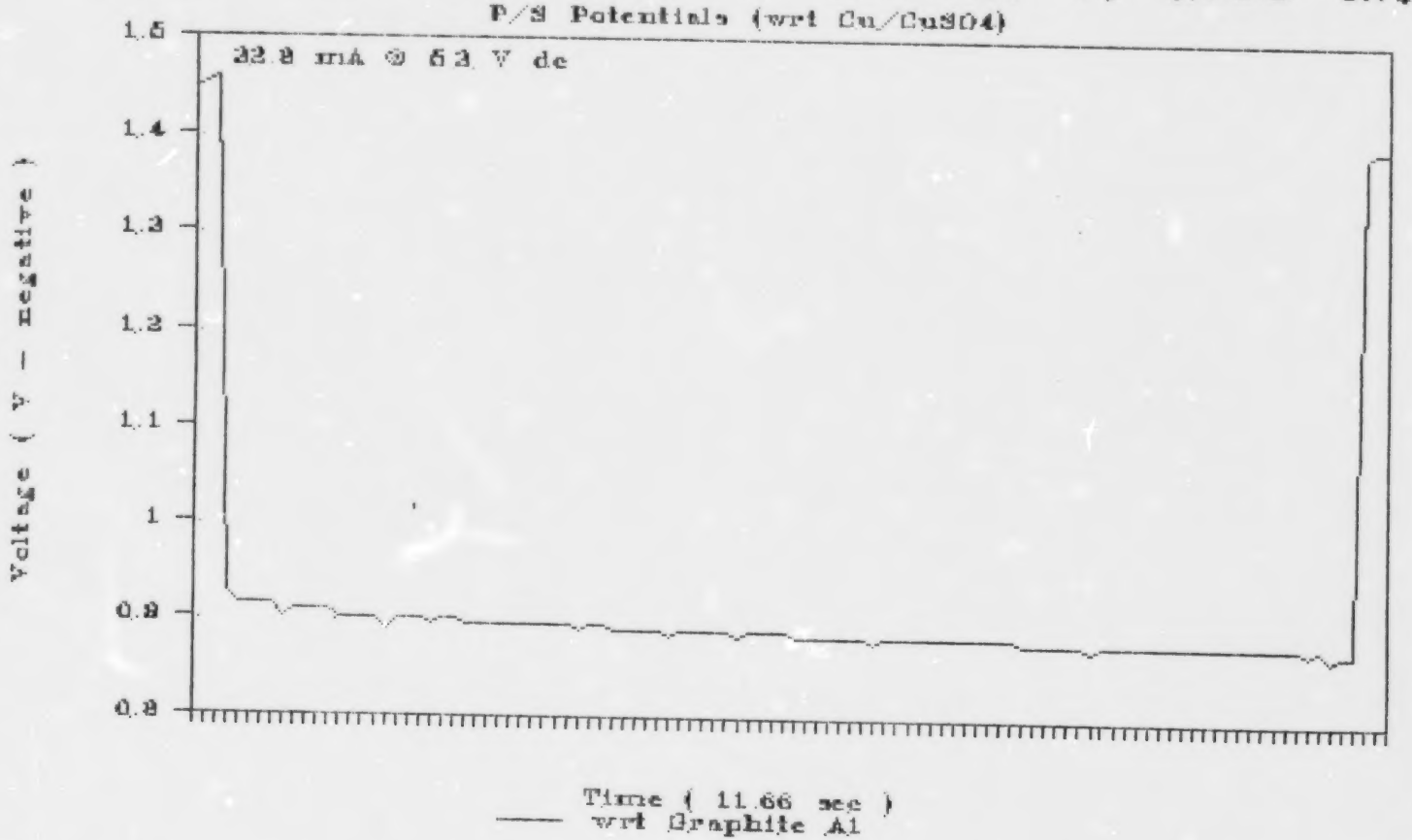


CANMET SPECIMEN # 1; MARCH 2, 1990 p.m.

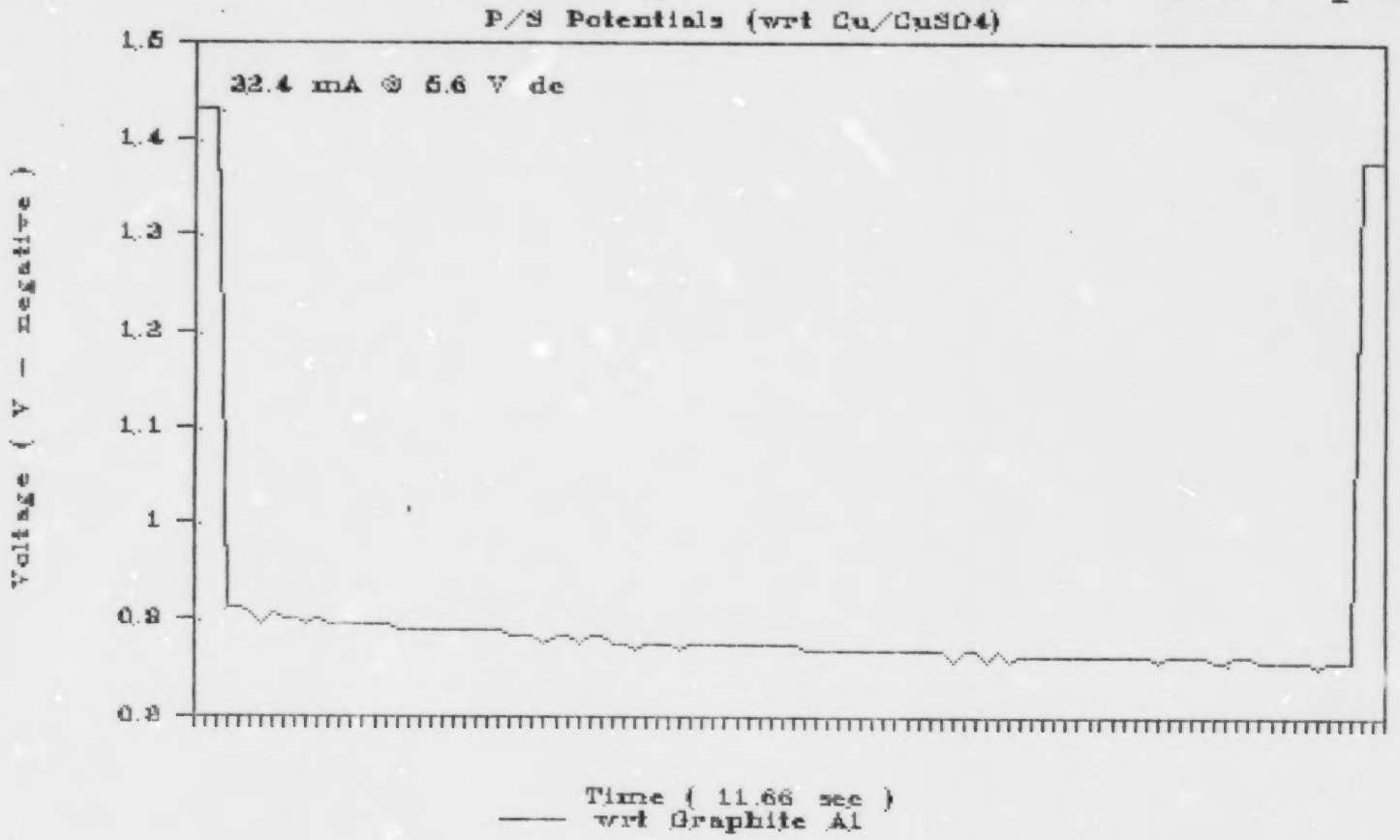


"Depolarization Curves - Graphite Reference A1"

CANMET SPECIMEN # 2; MARCH 8, 1990 a.m.



CANMET SPECIMEN # 2; MARCH 8, 1990 p.m.



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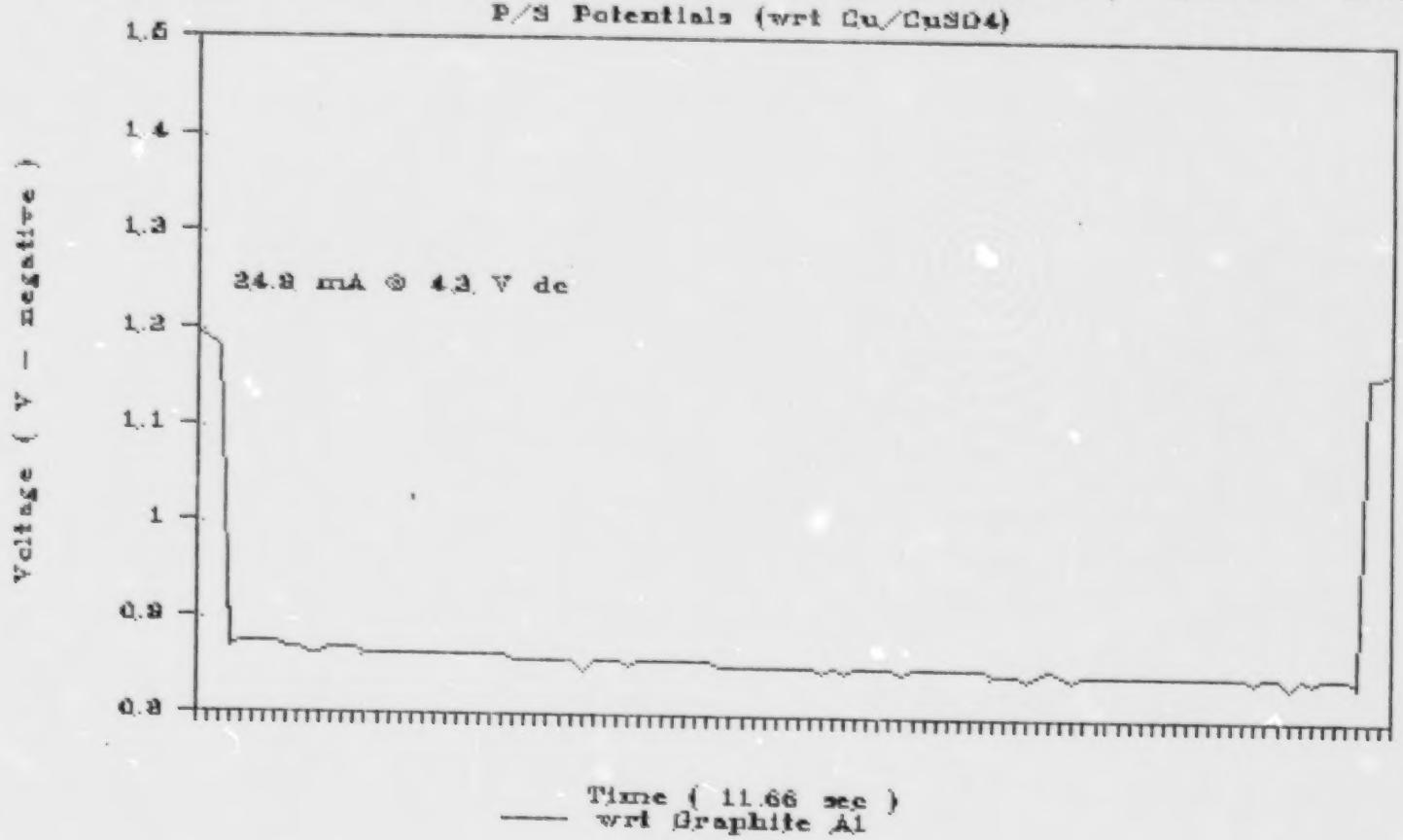
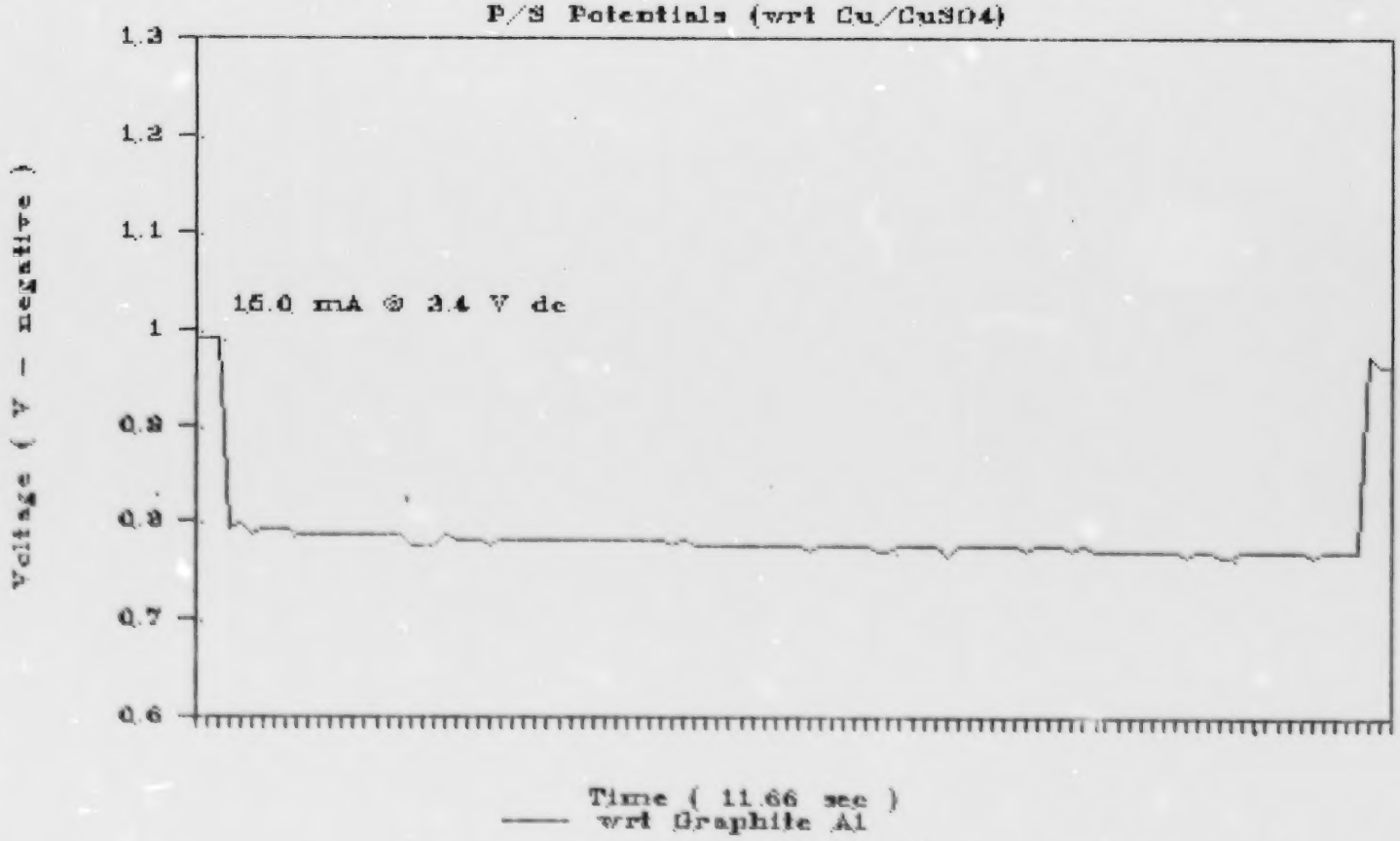
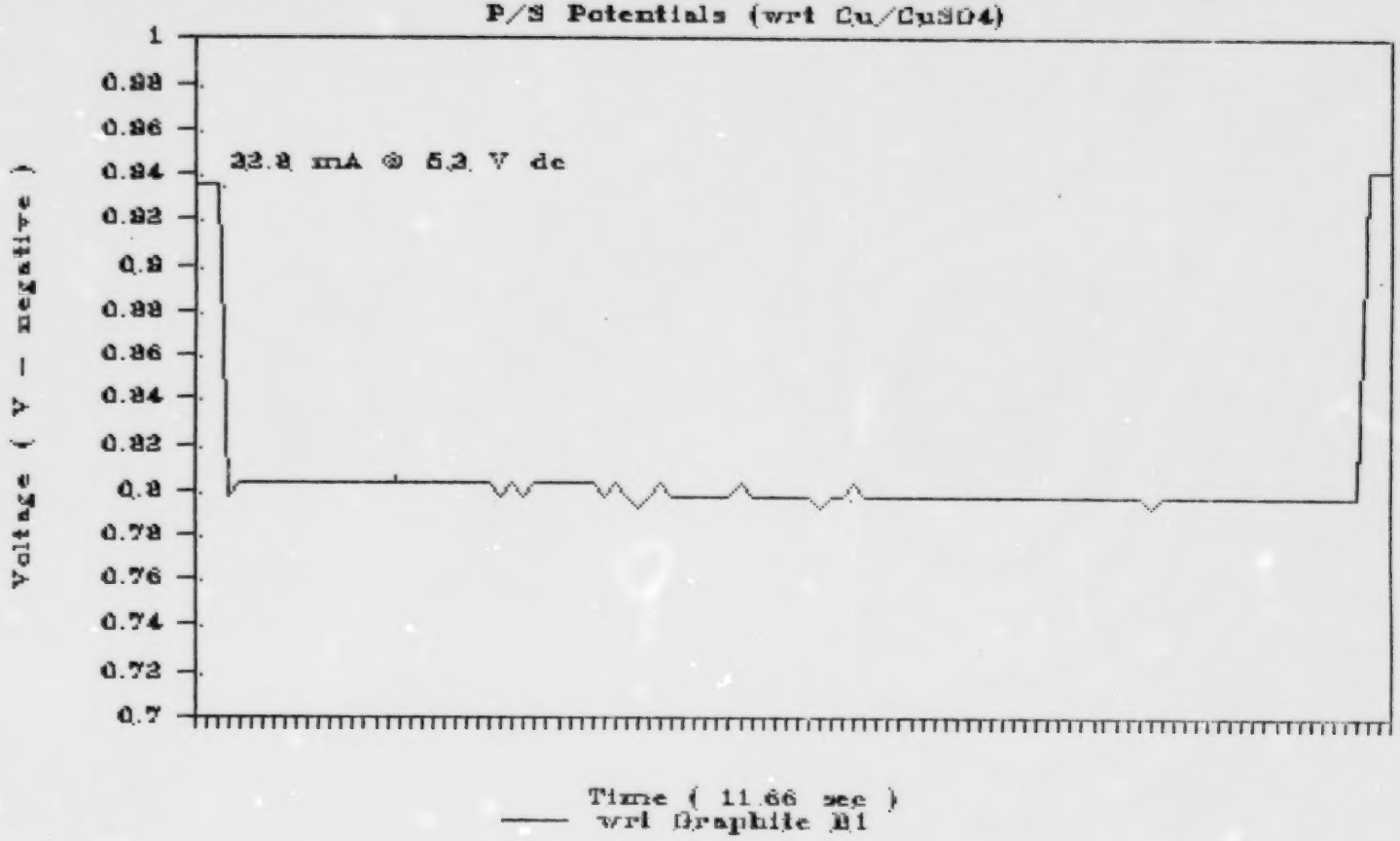


CANMET SPECIMEN # 2; MARCH 9, 1990 p.m.

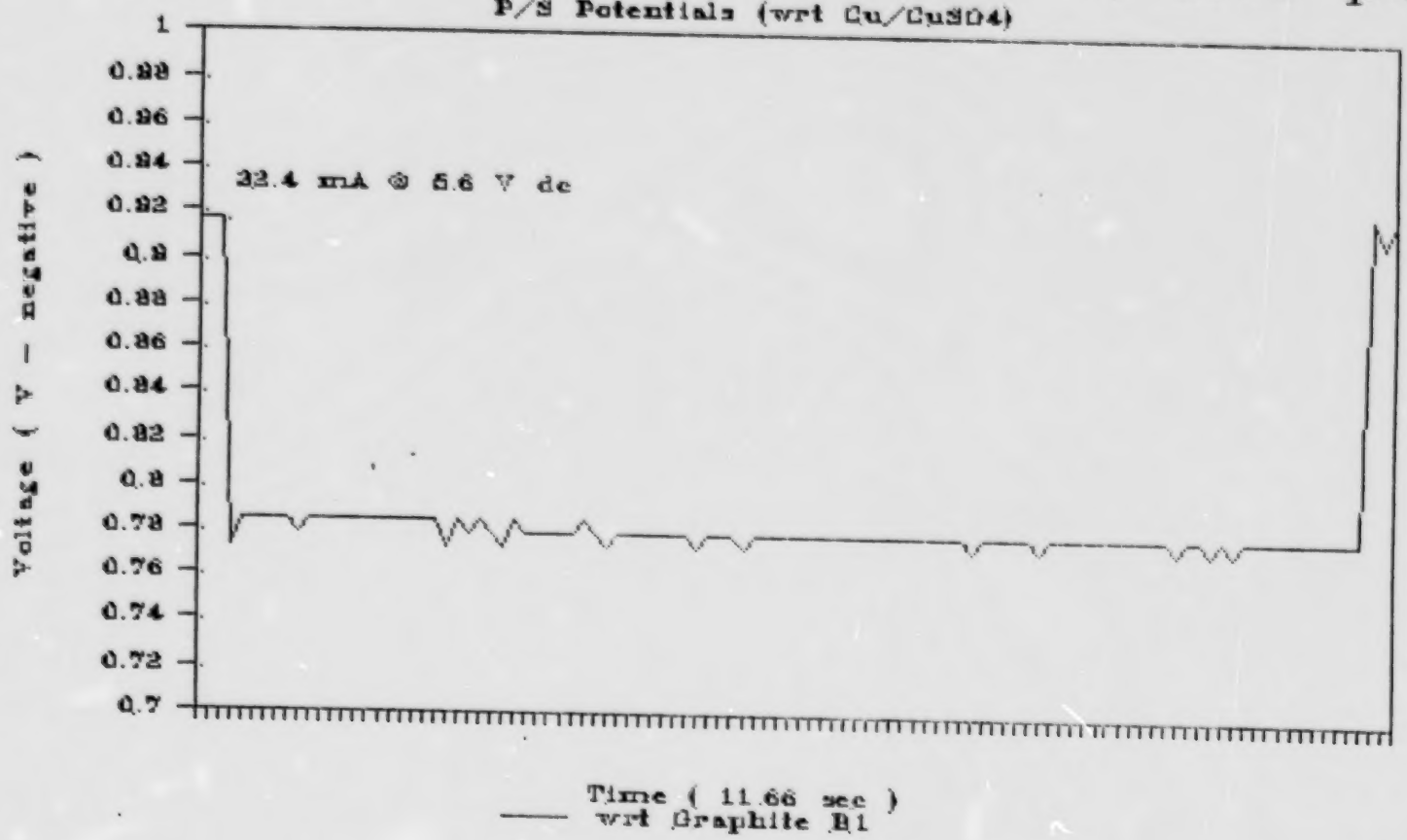


"Depolarization Curves - Graphite Reference B1"

CANMET SPECIMEN # 2; MARCH 8, 1990 a.m.



CANMET SPECIMEN # 2; MARCH 8, 1990 p.m.



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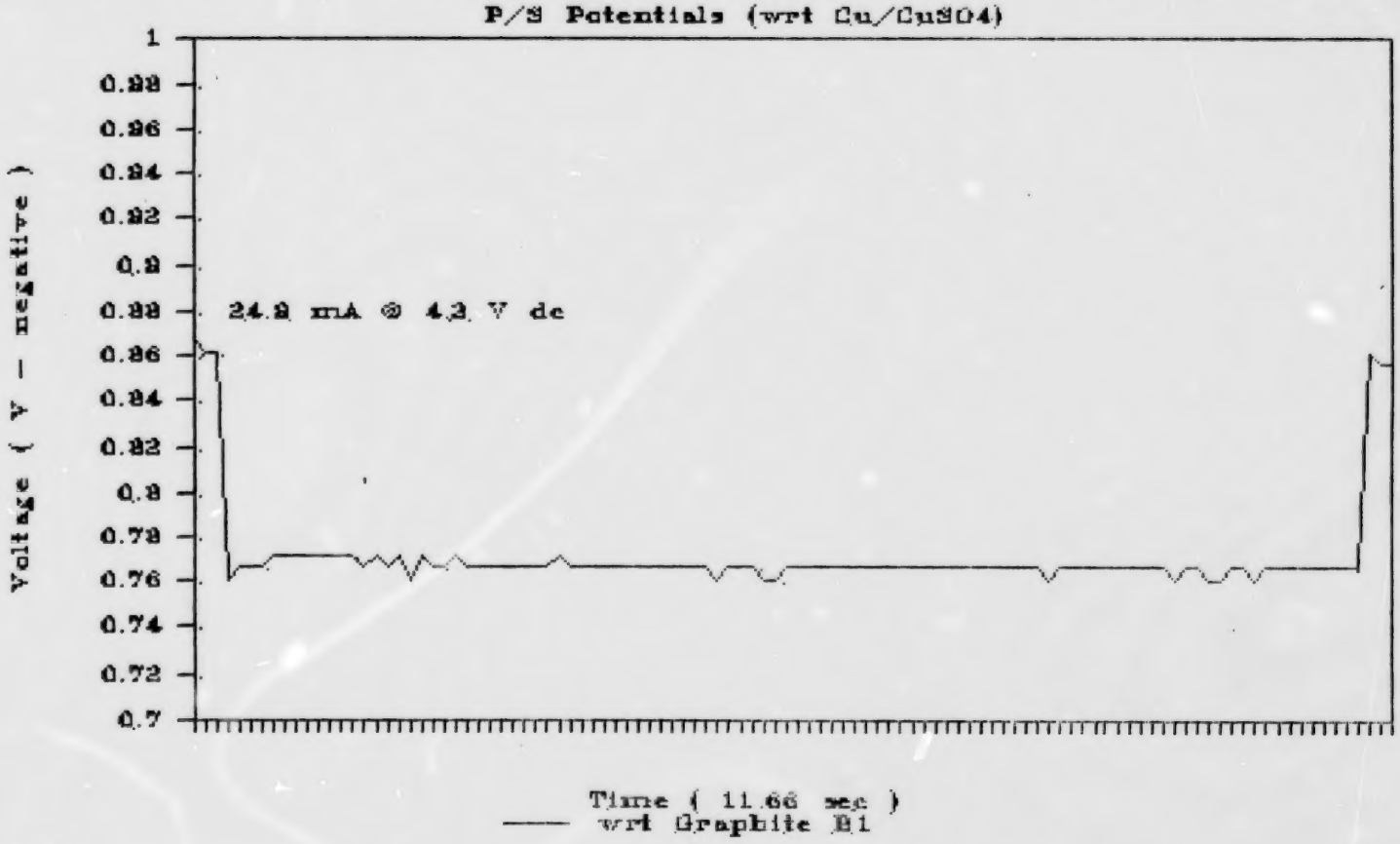
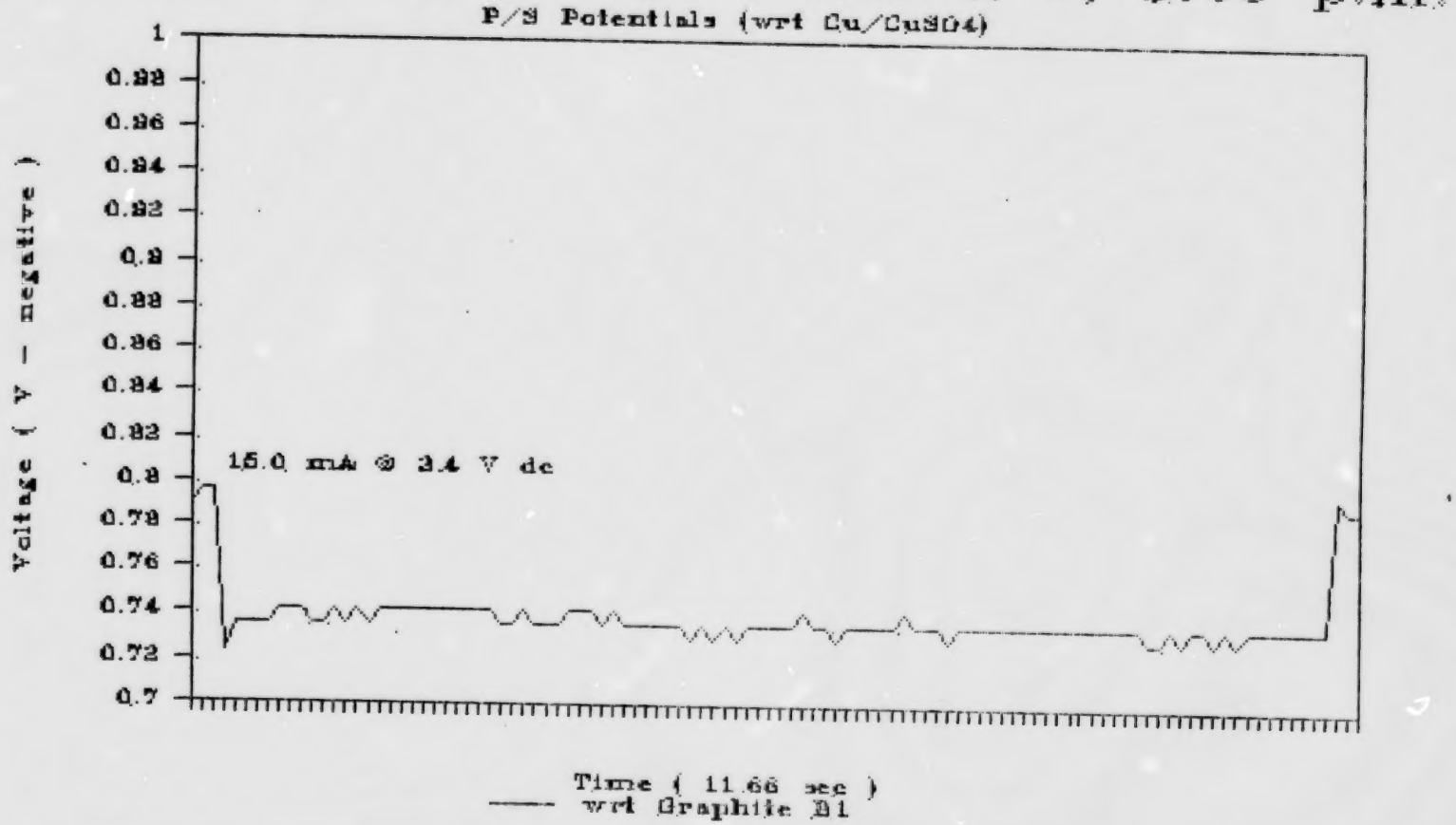


CANMET SPECIMEN # 2; MARCH 9, 1990 p.m.



"Depolarization Curves - Graphite Reference A2"

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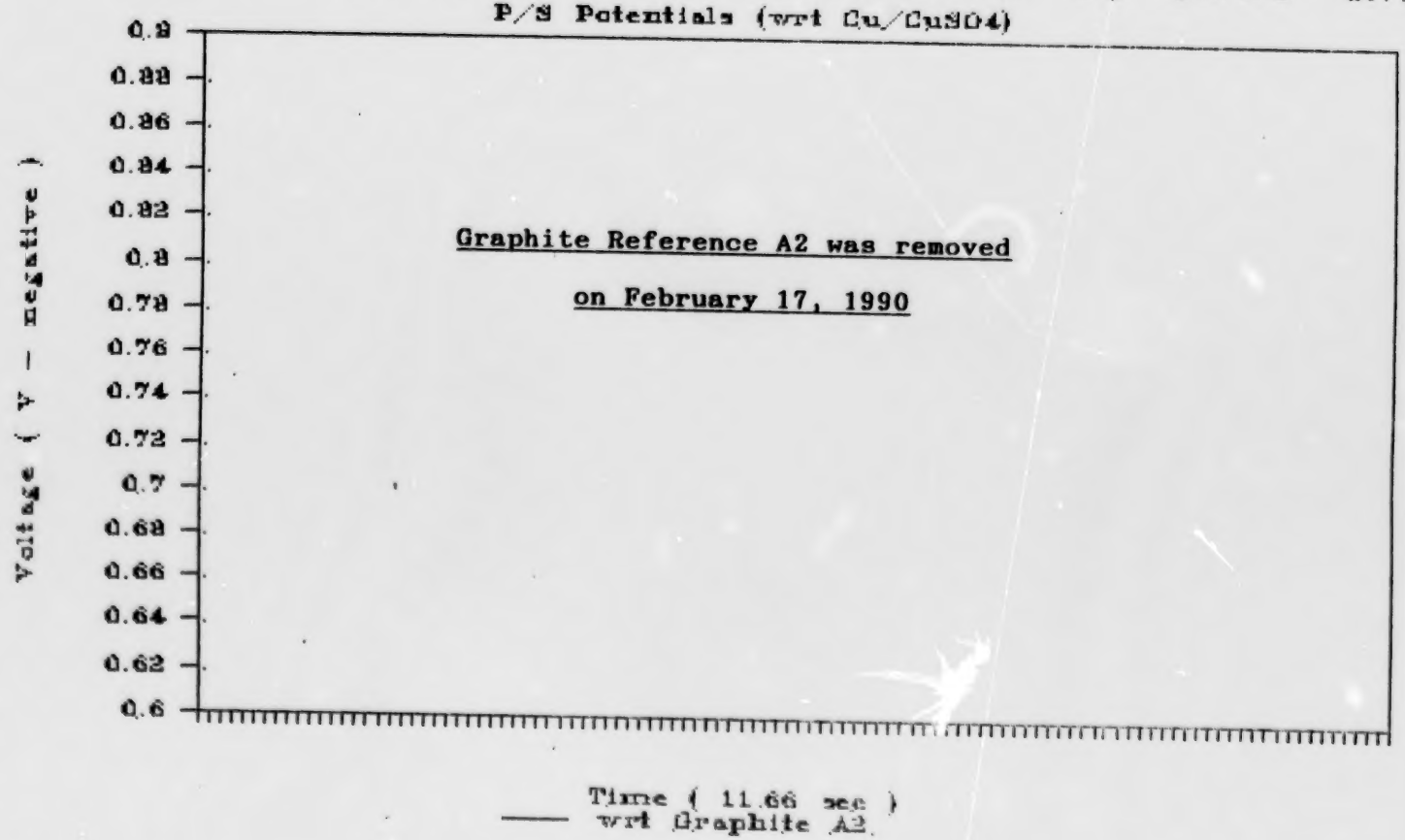

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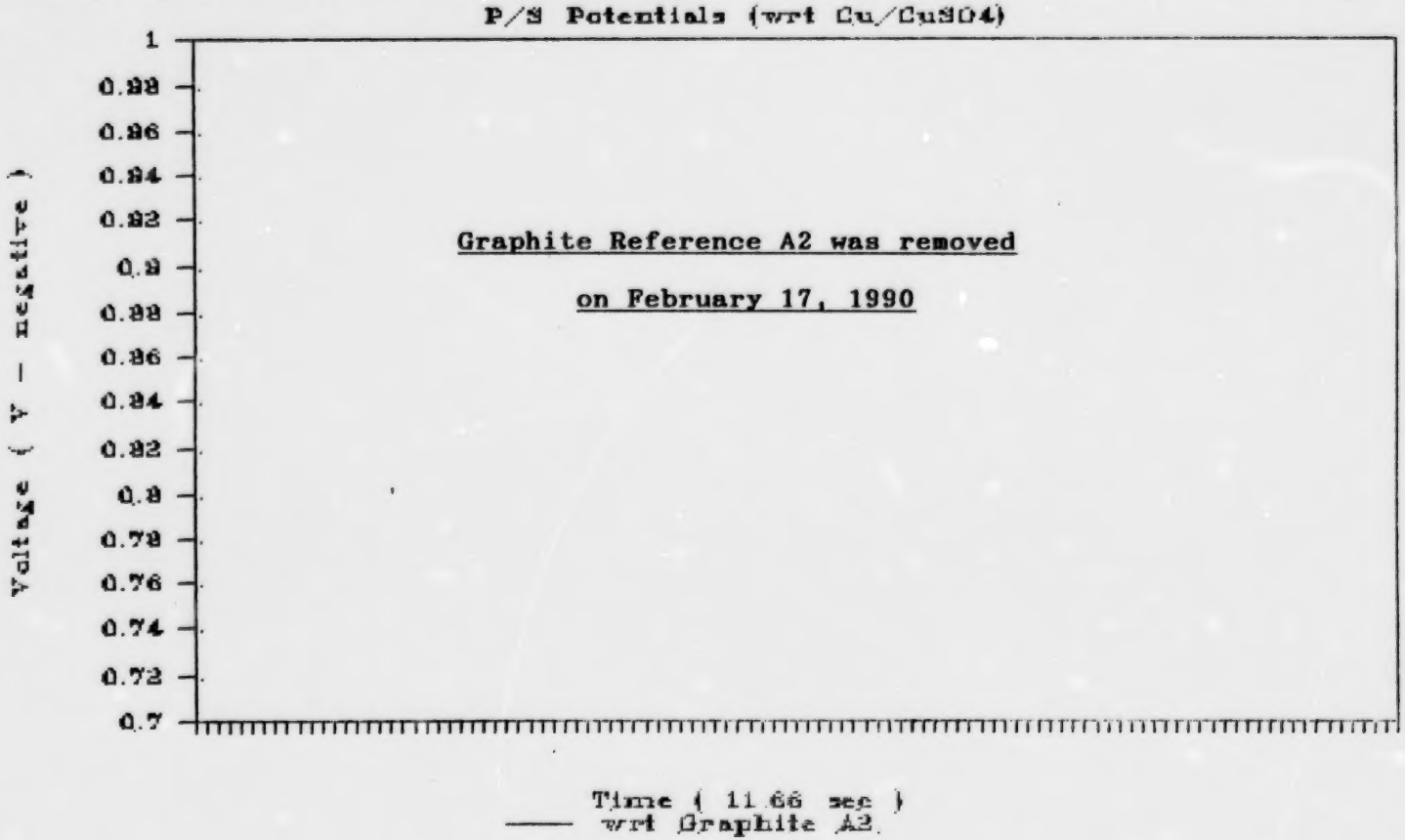

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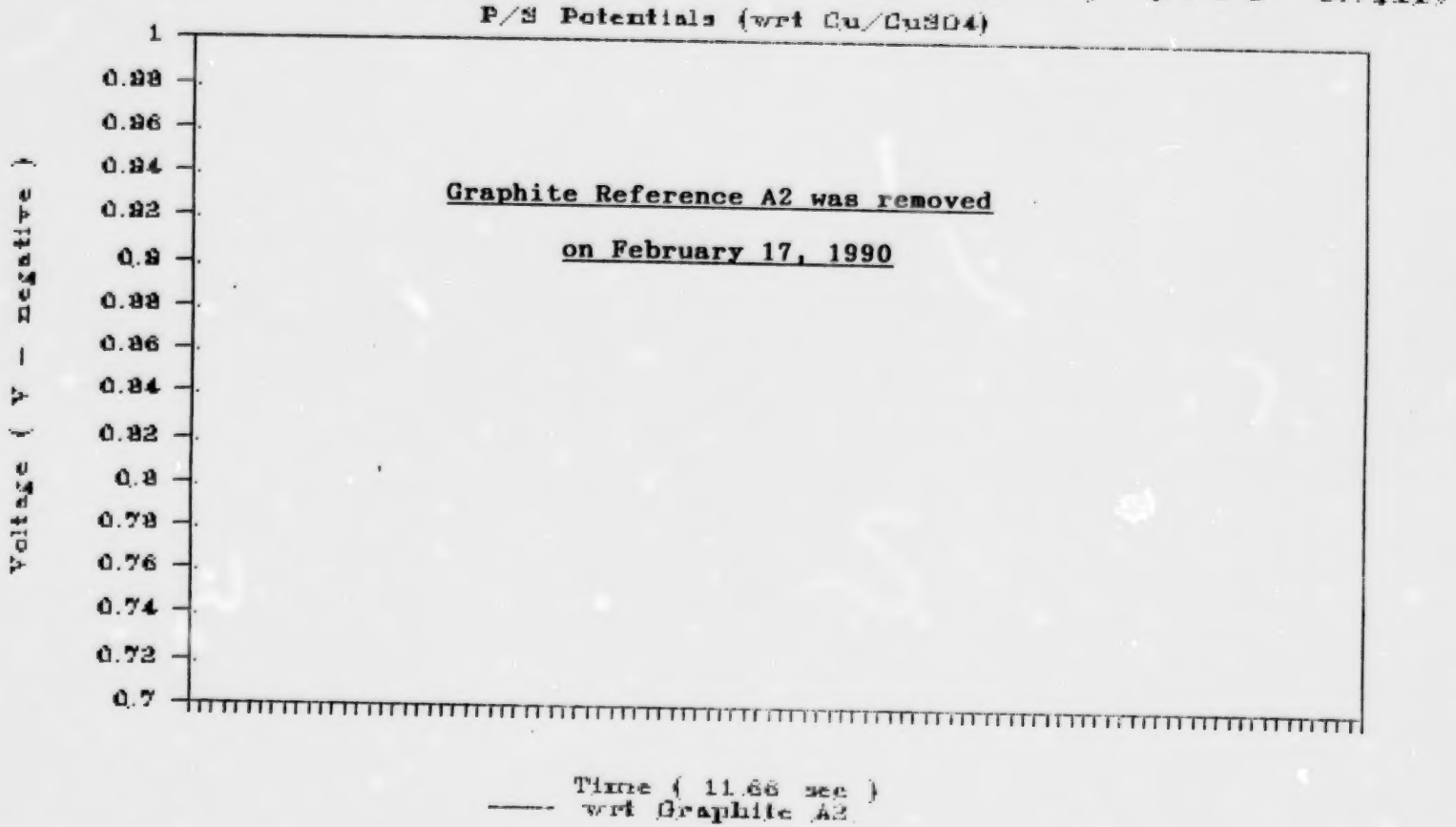
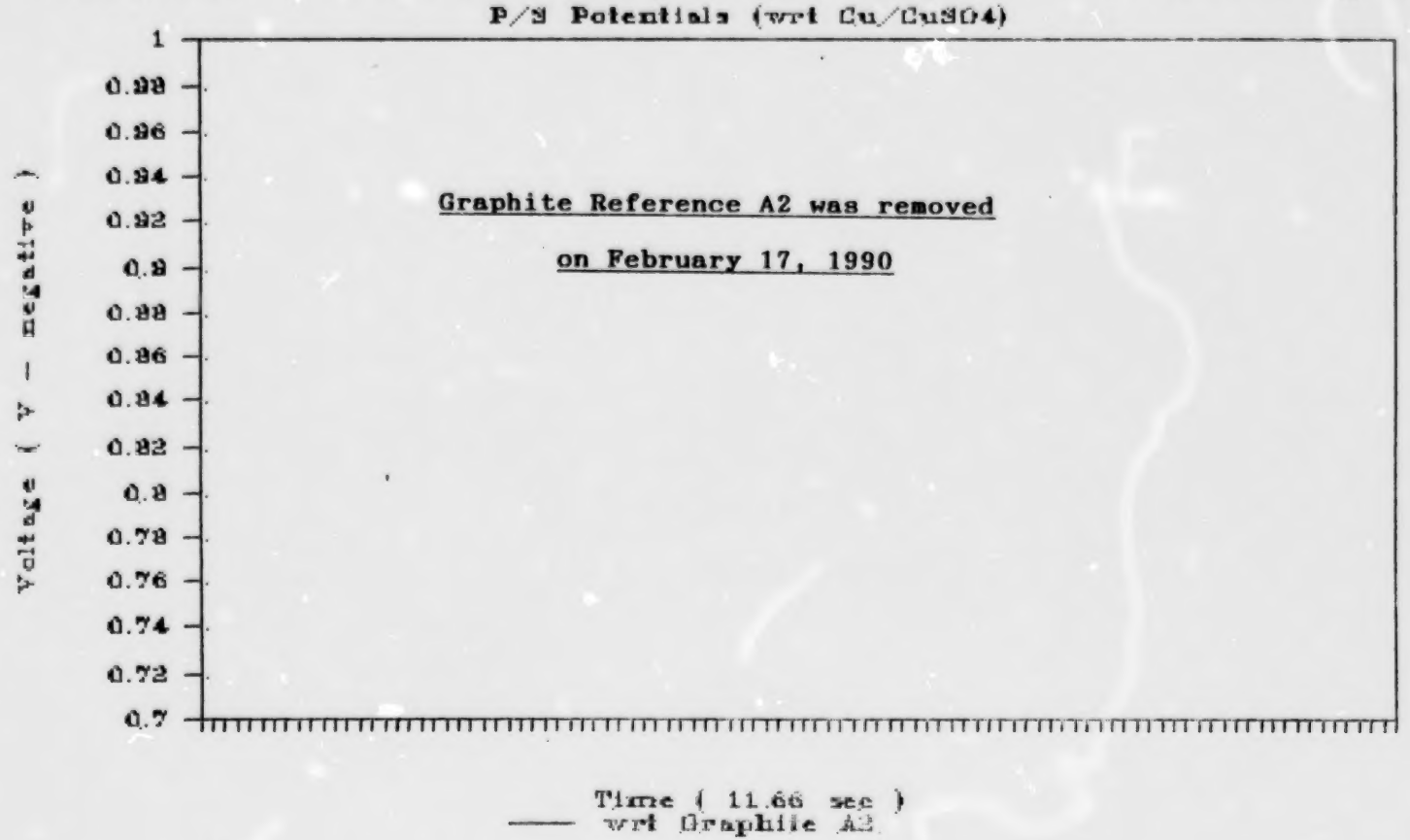
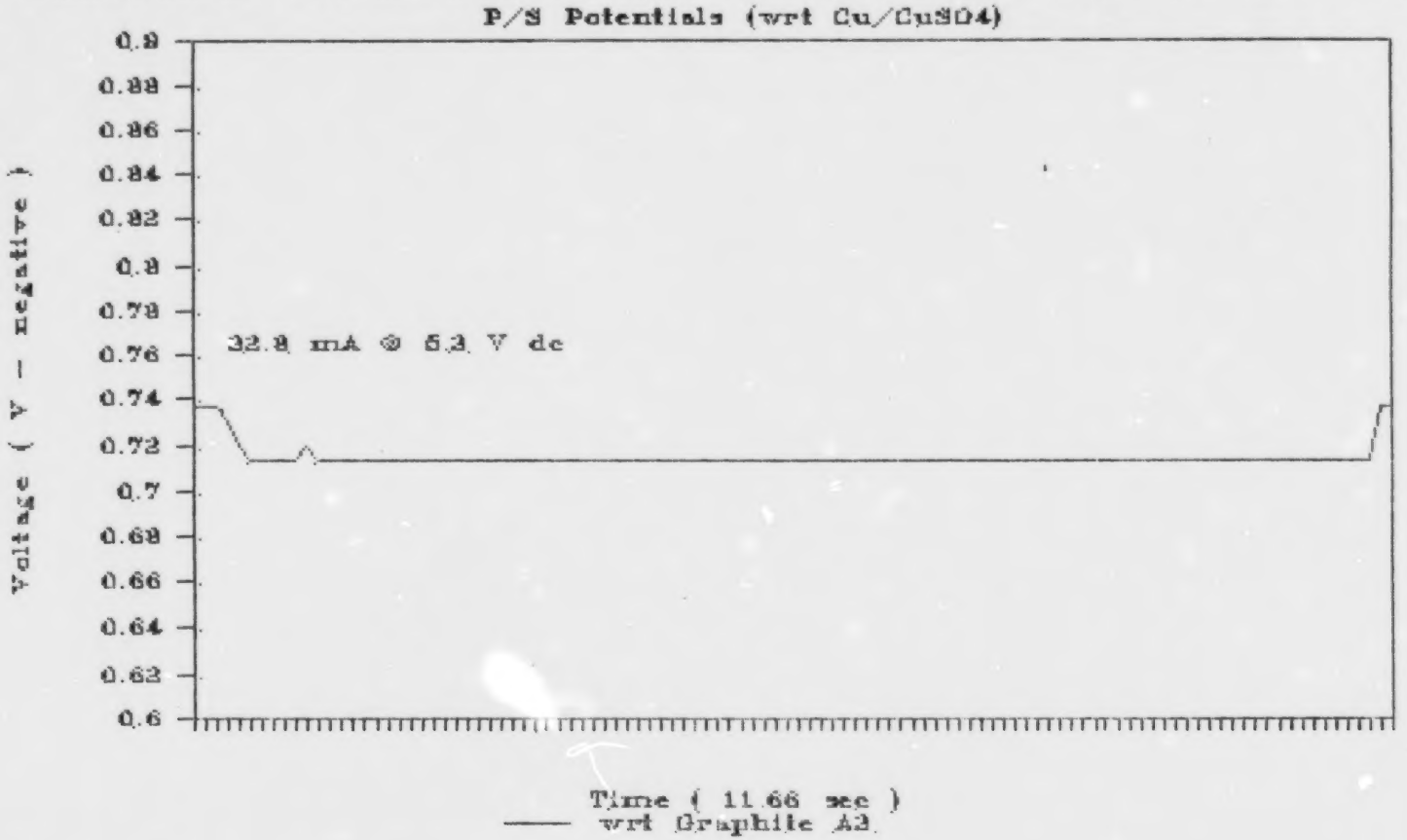


CANMET SPECIMEN # 2; MARCH 9, 1990 p.m.

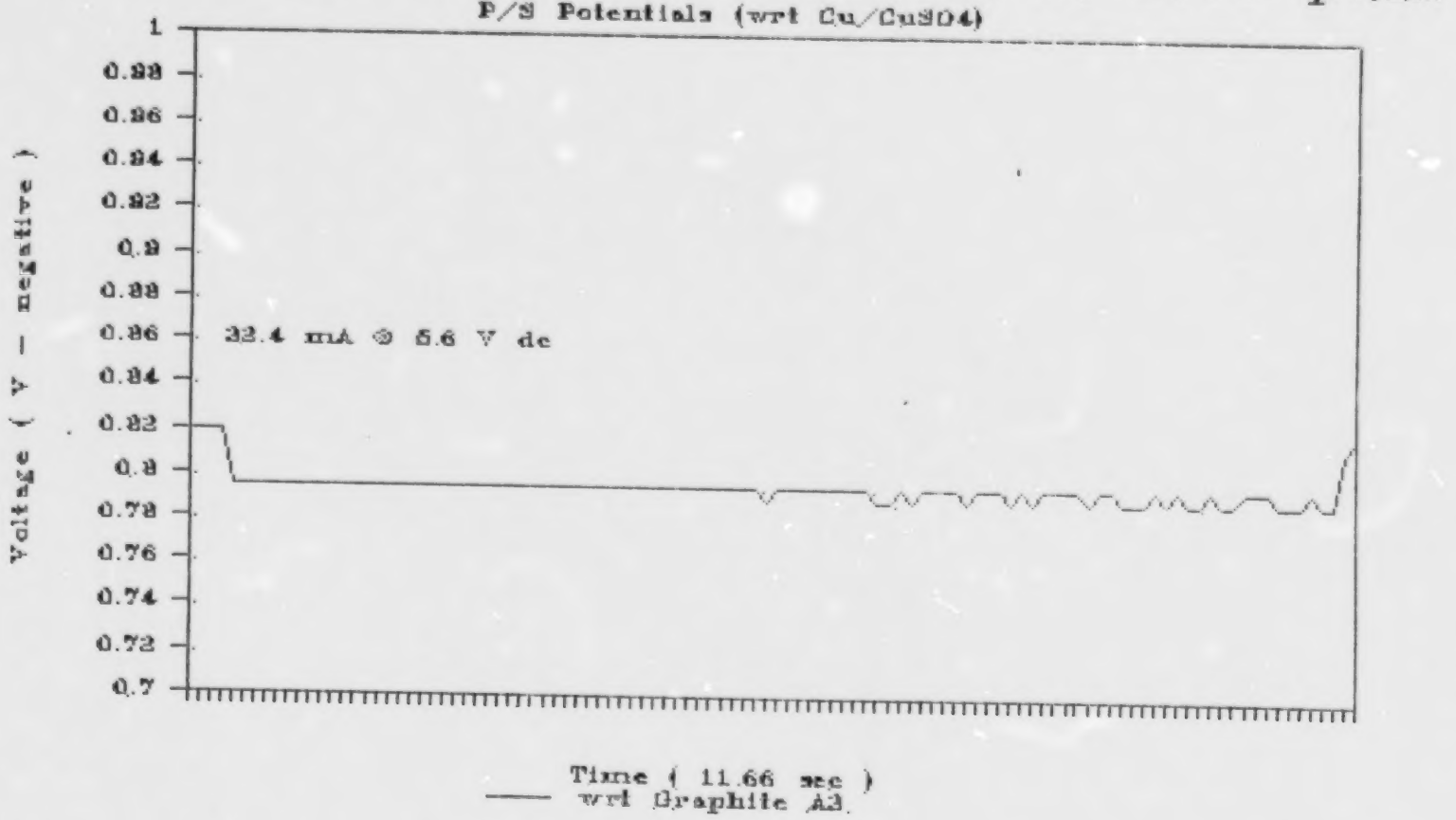


"Depolarization Curves - Graphite Reference A3"

CANMET SPECIMEN # 2; MARCH 8, 1990 a.m.



CANMET SPECIMEN # 2; MARCH 8, 1990 p.m.



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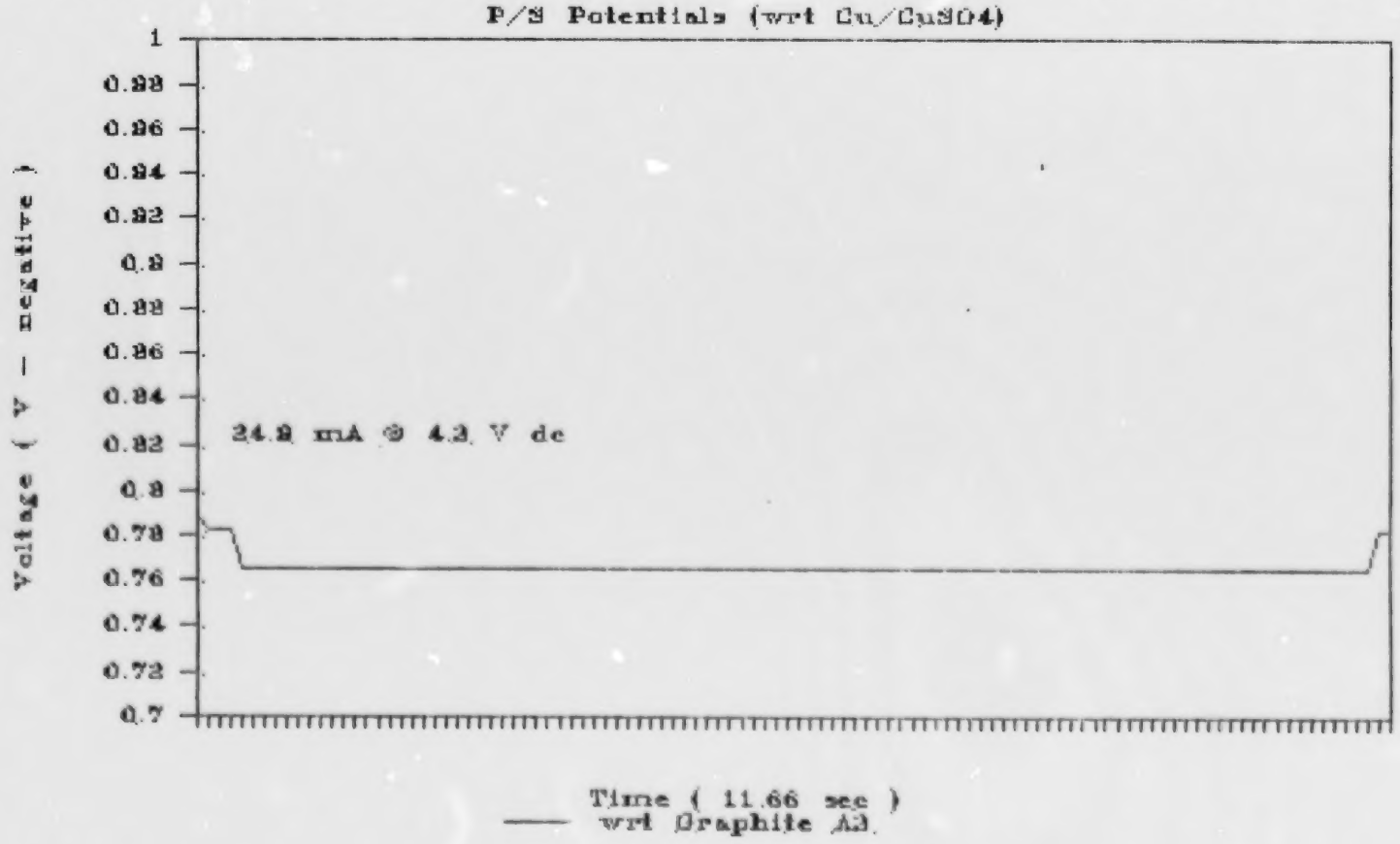
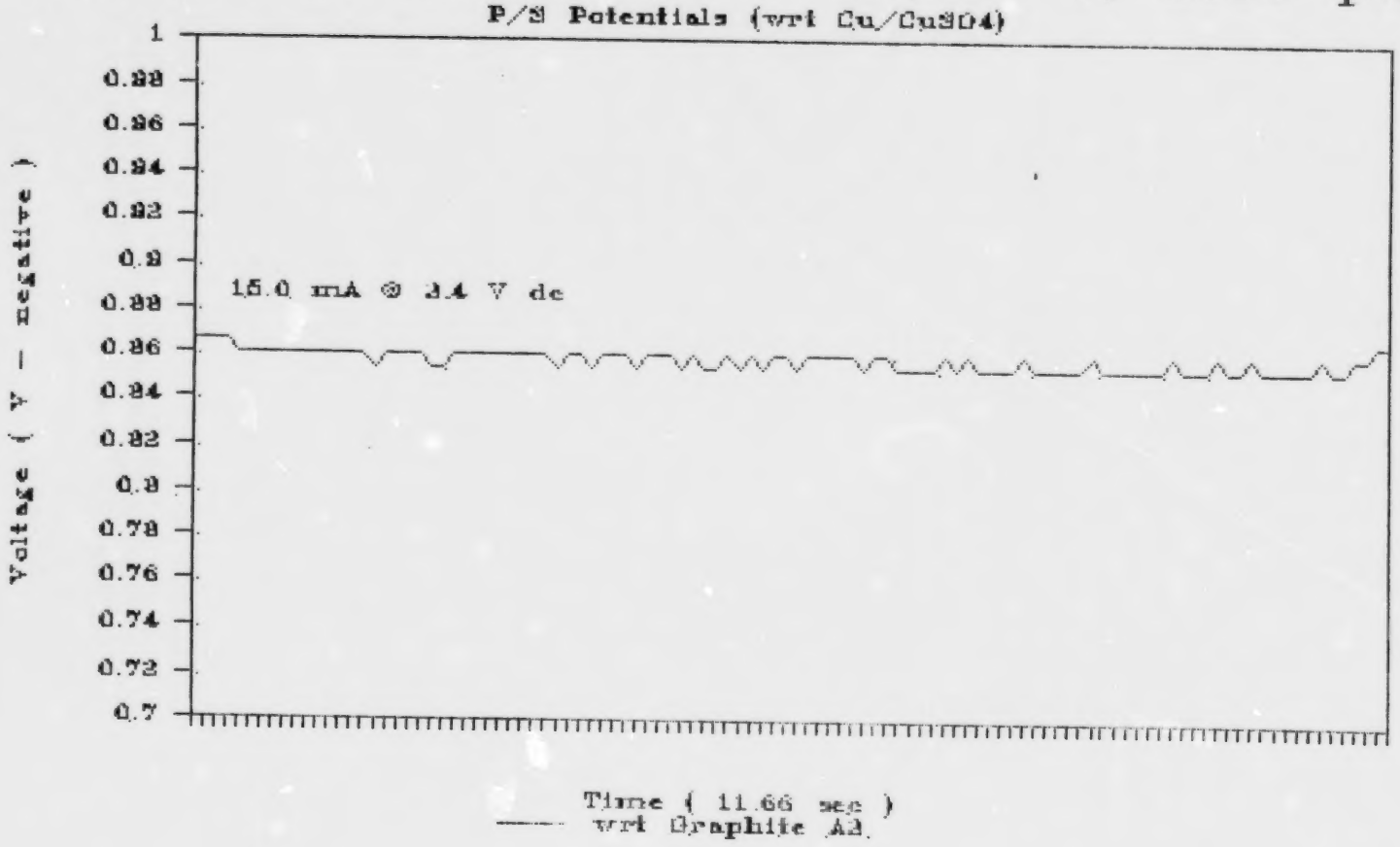
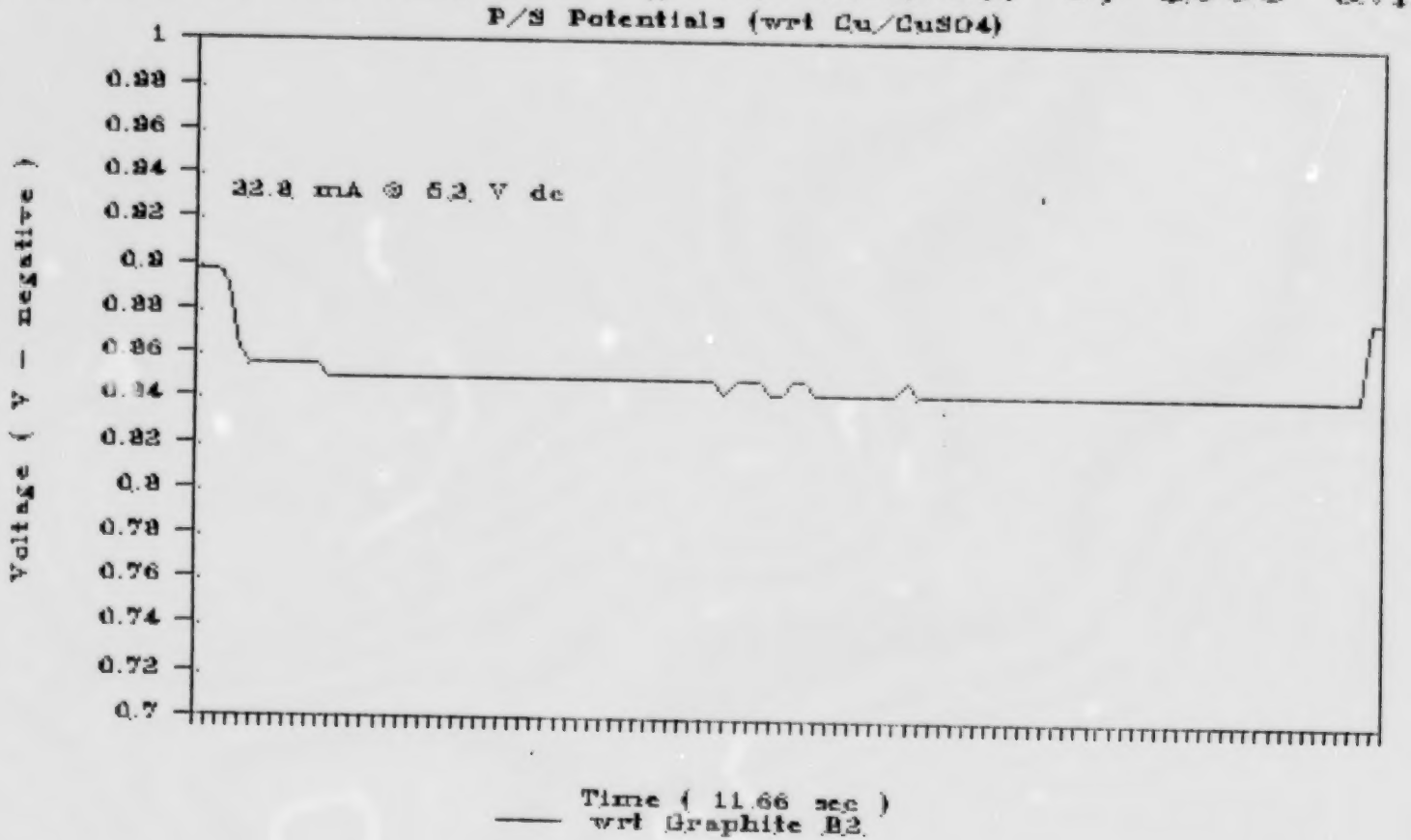


CANMET SPECIMEN # 2; MARCH 9, 1990 p.m.

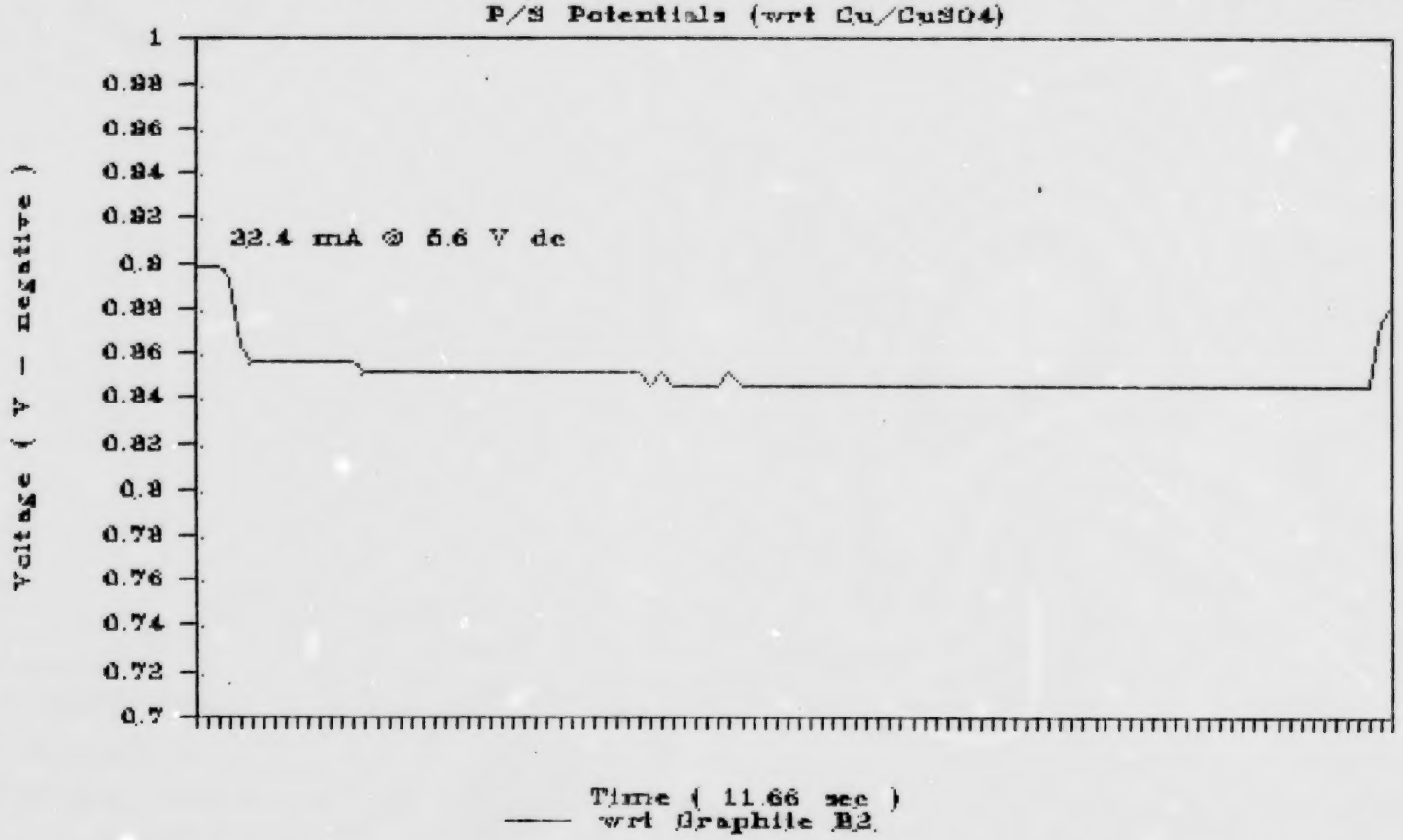


"Depolarization Curves - Graphite Reference B2"

CANMET SPECIMEN # 2; MARCH 8, 1990 a.m.



CANMET SPECIMEN # 2; MARCH 8, 1990 p.m.



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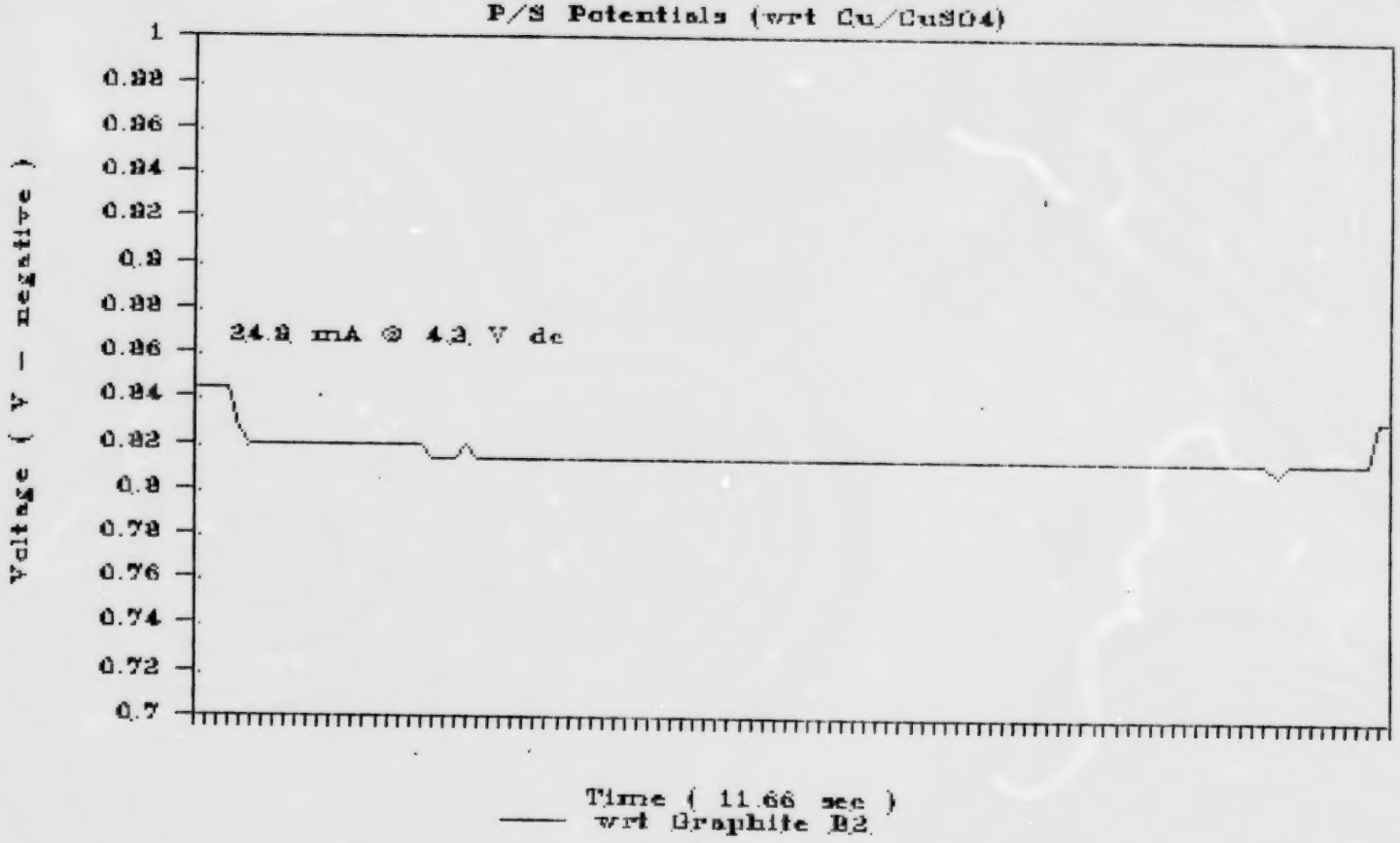
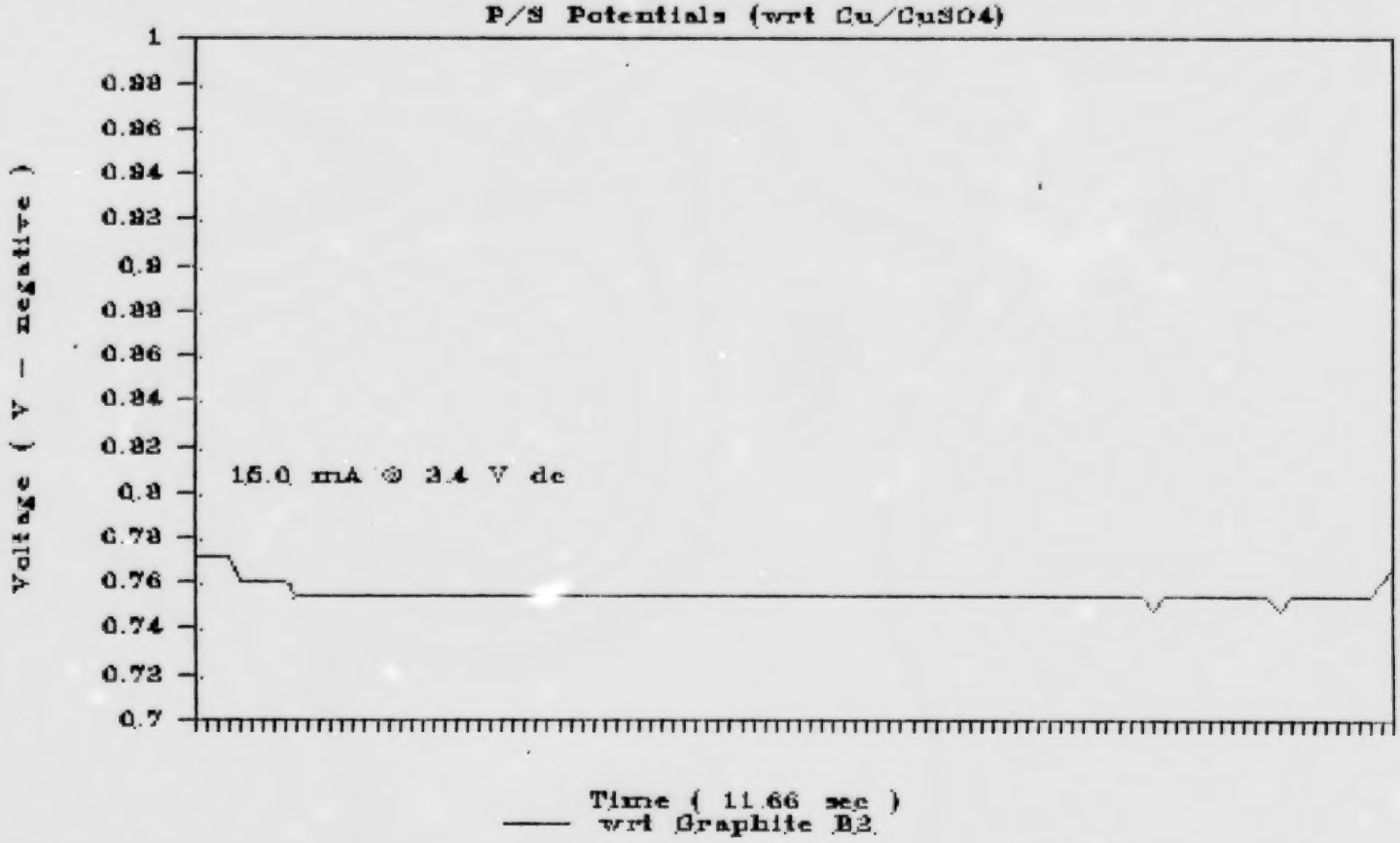


CANMET SPECIMEN # 2; MARCH 9, 1990 p.m.



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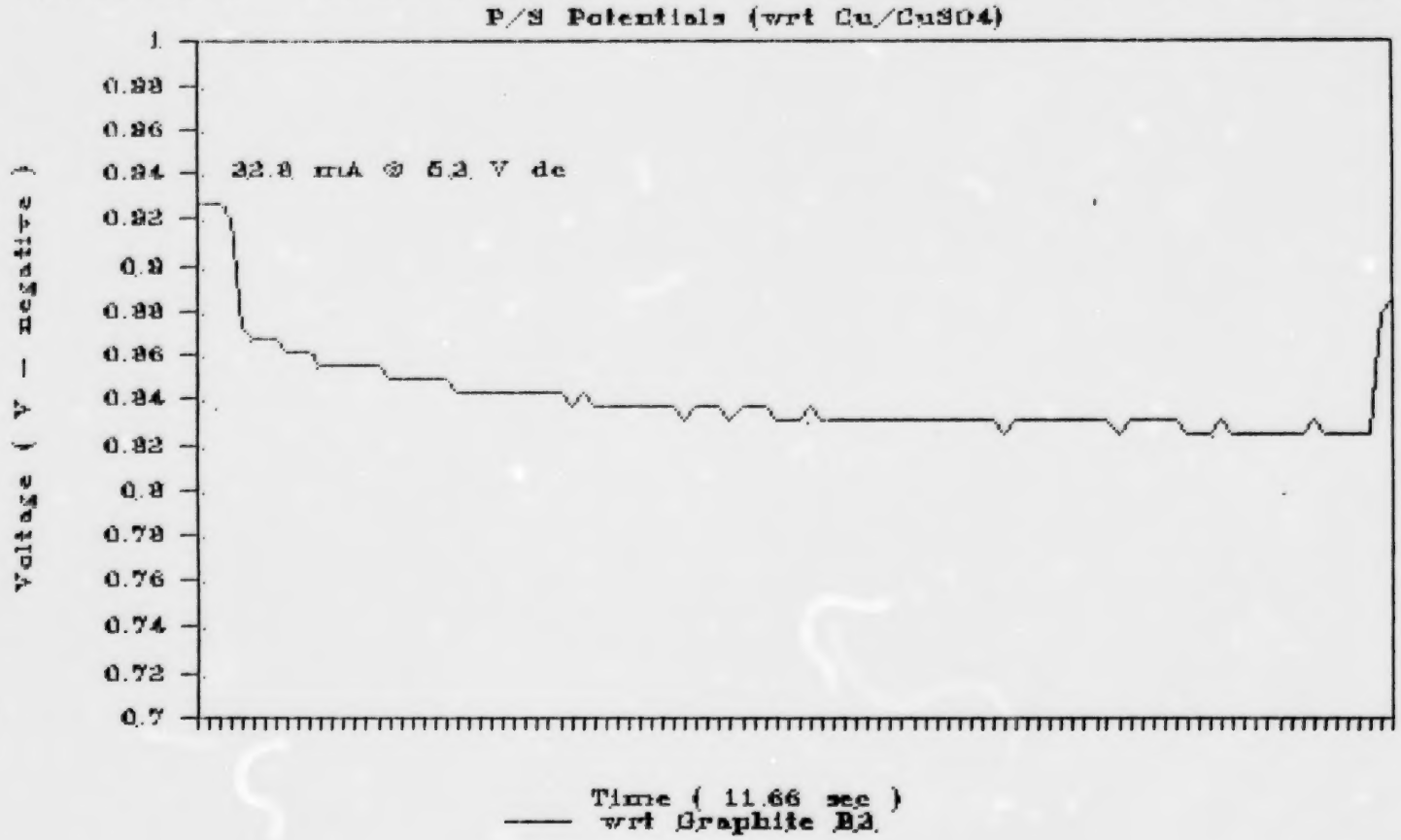

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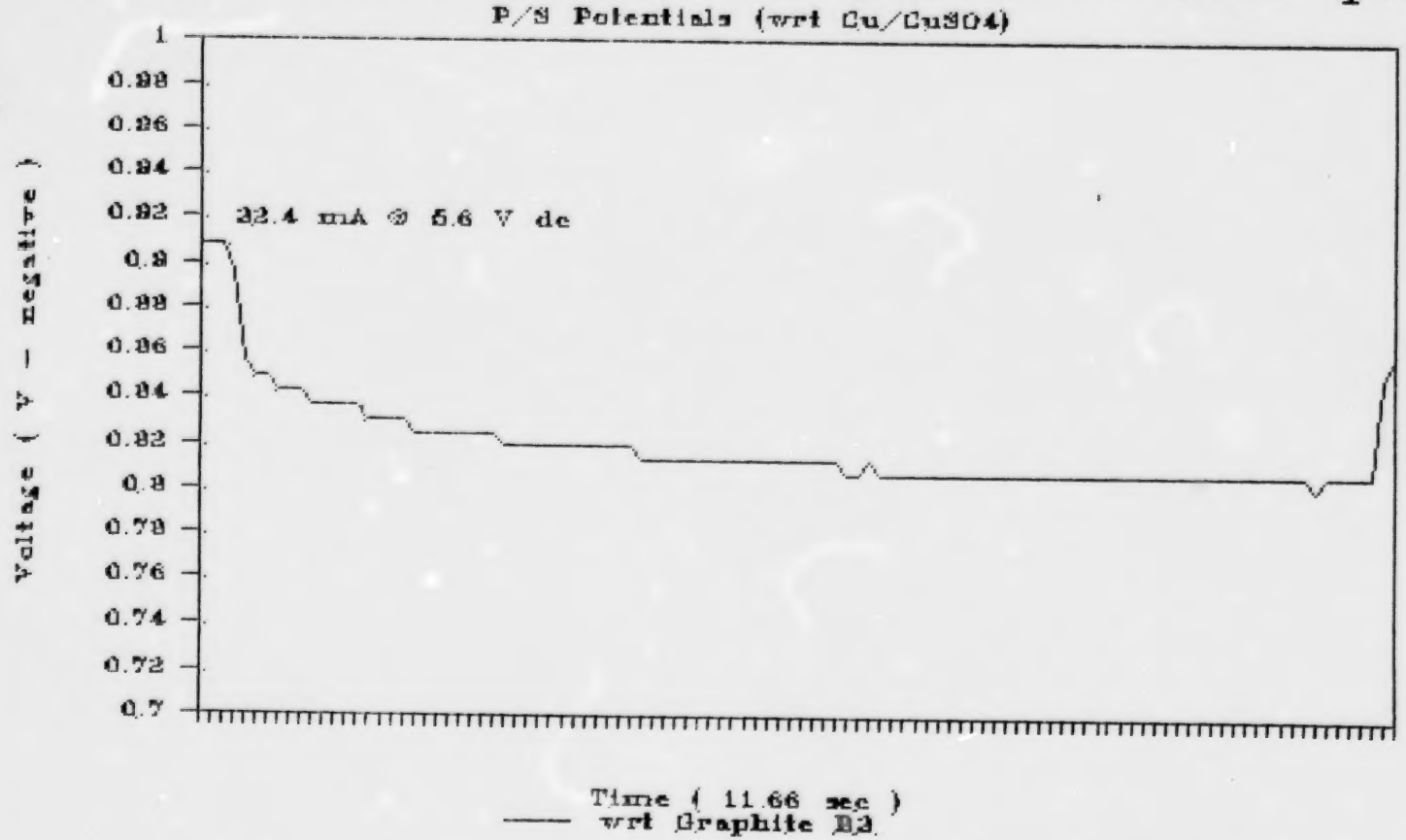

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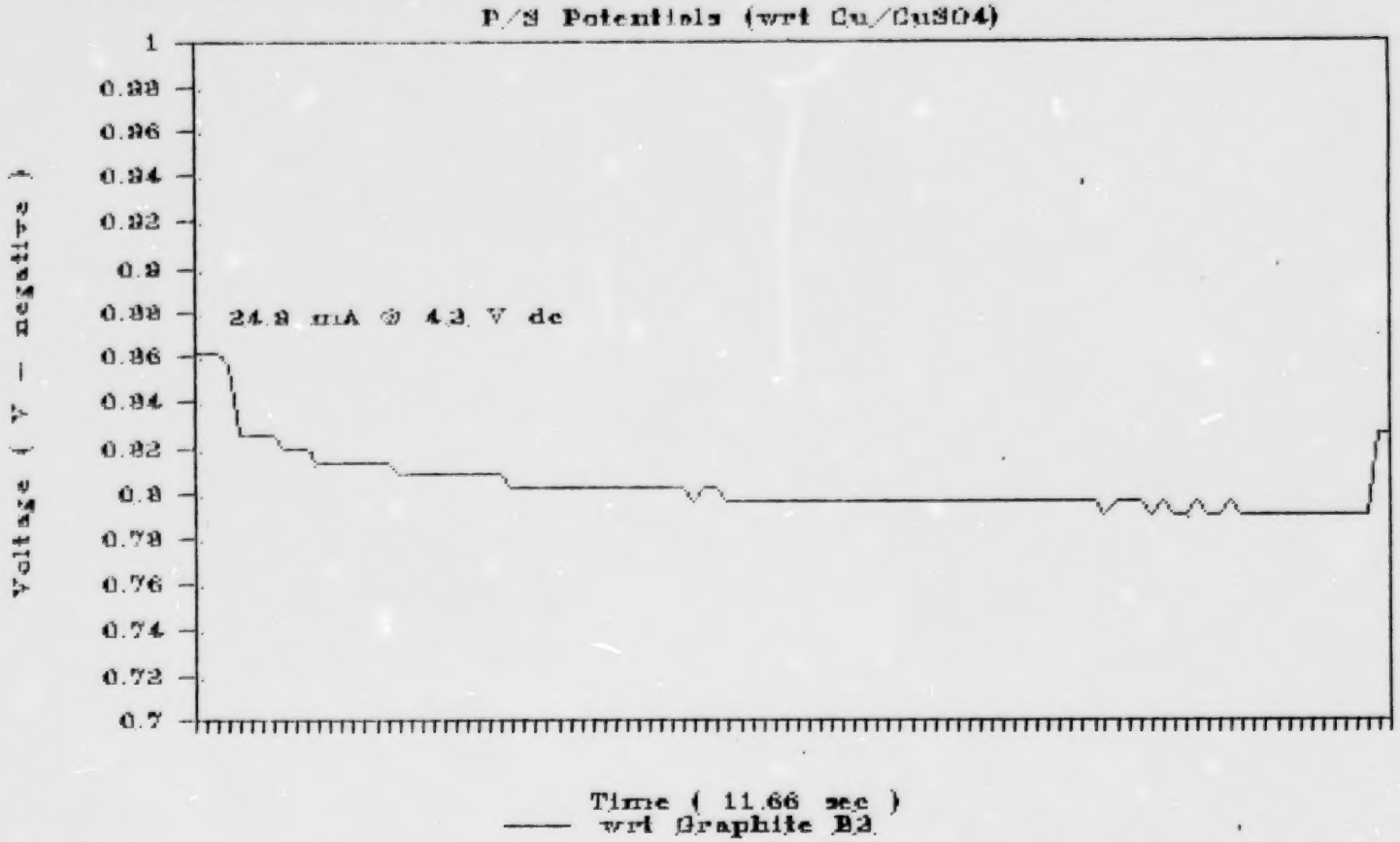

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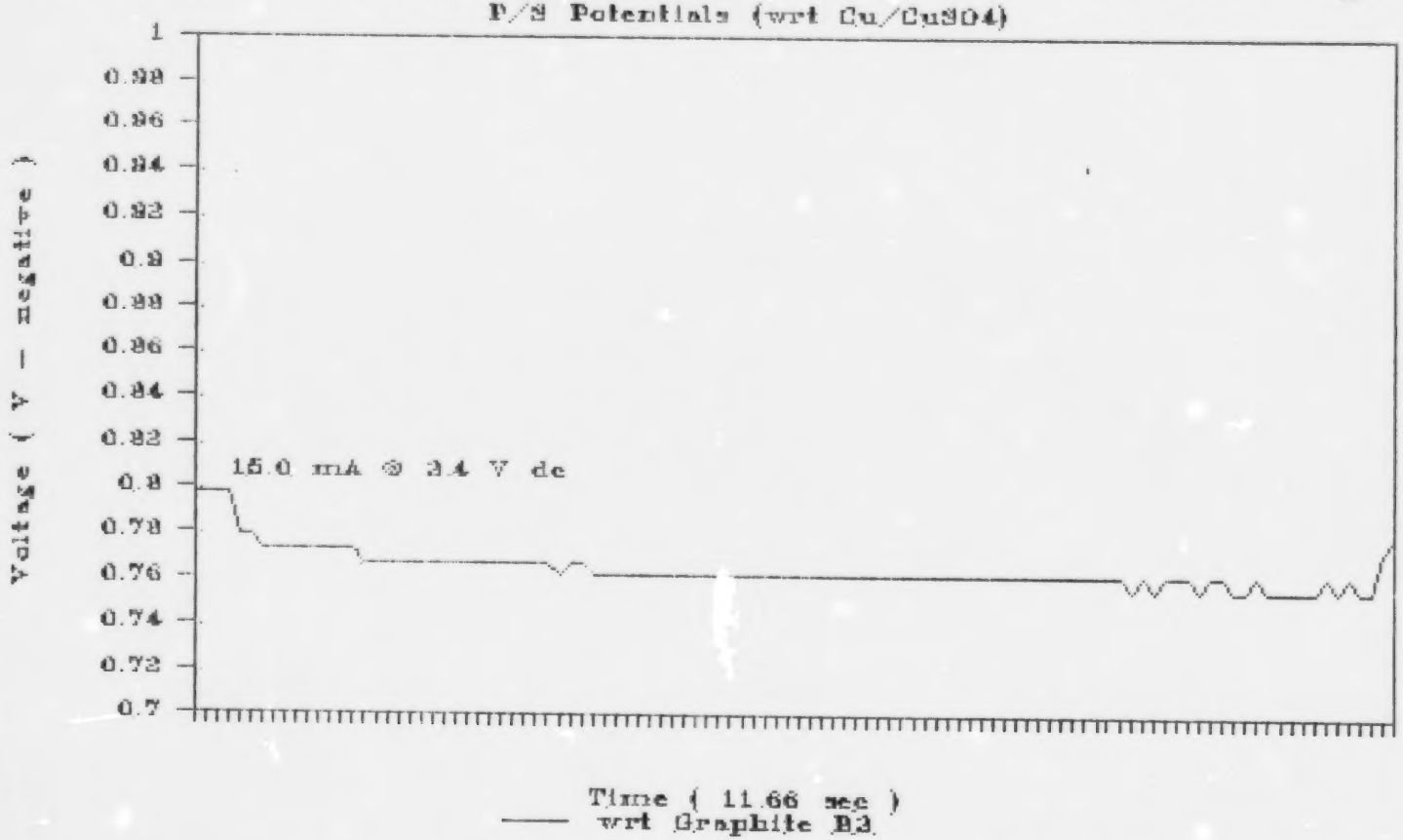

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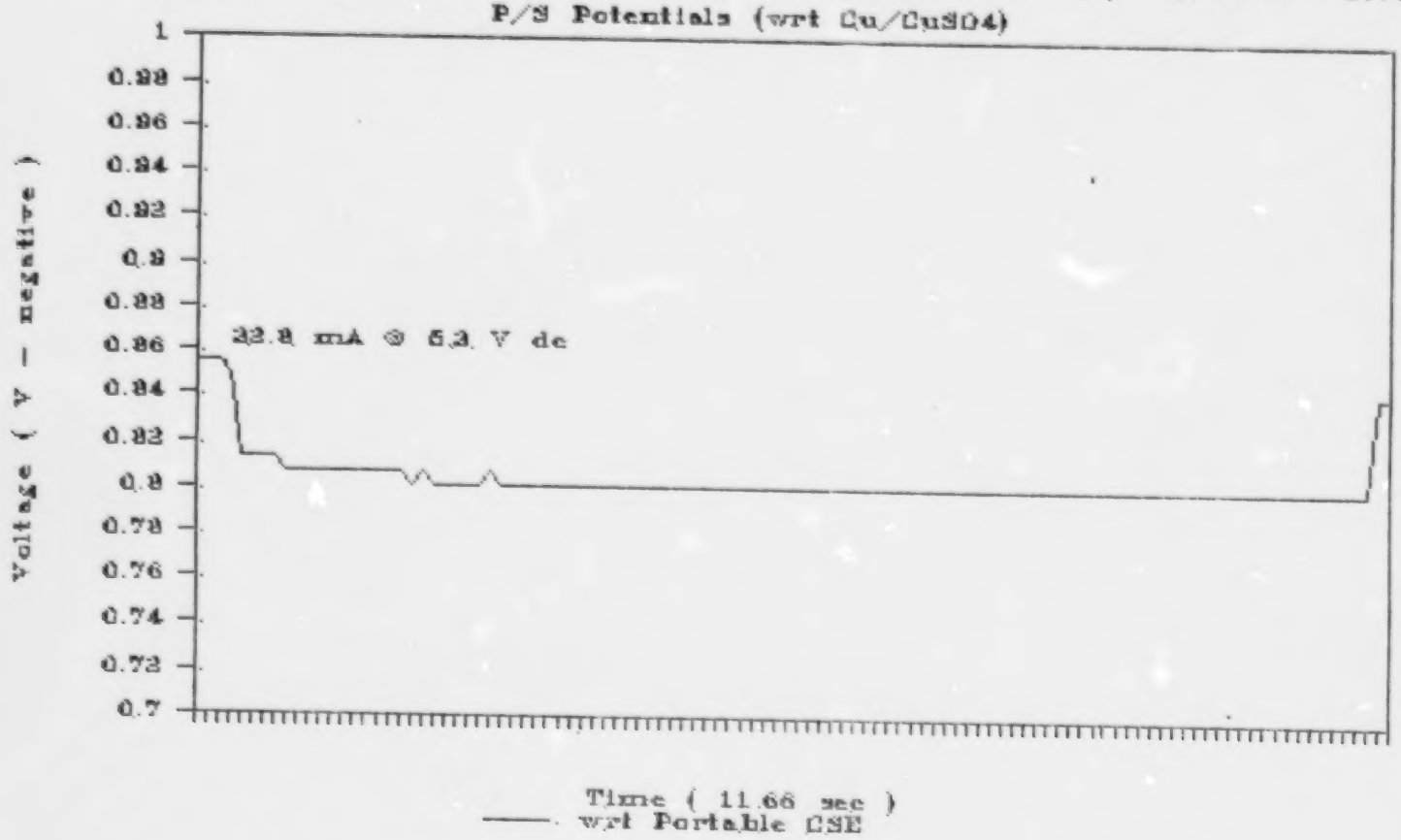

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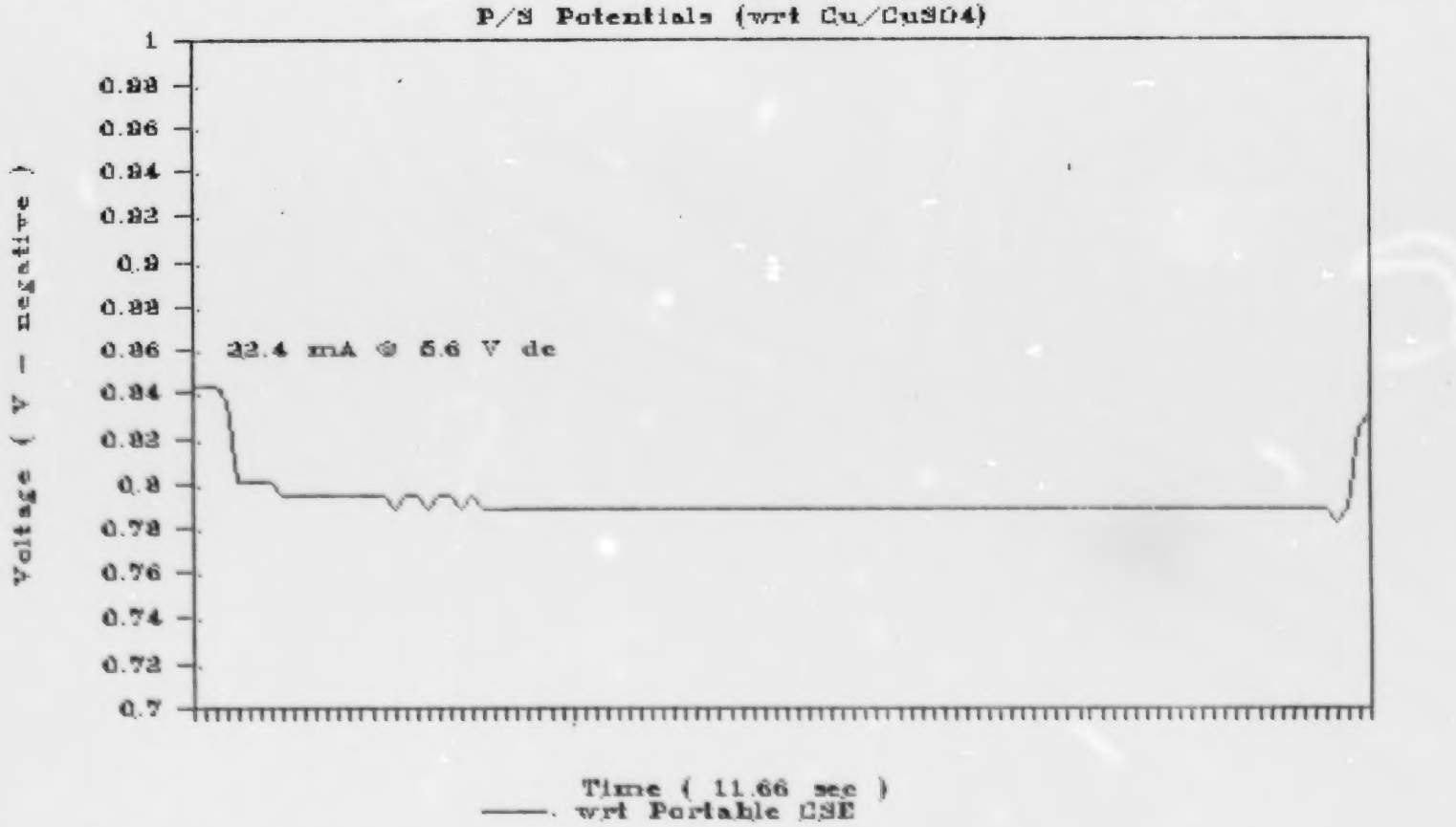

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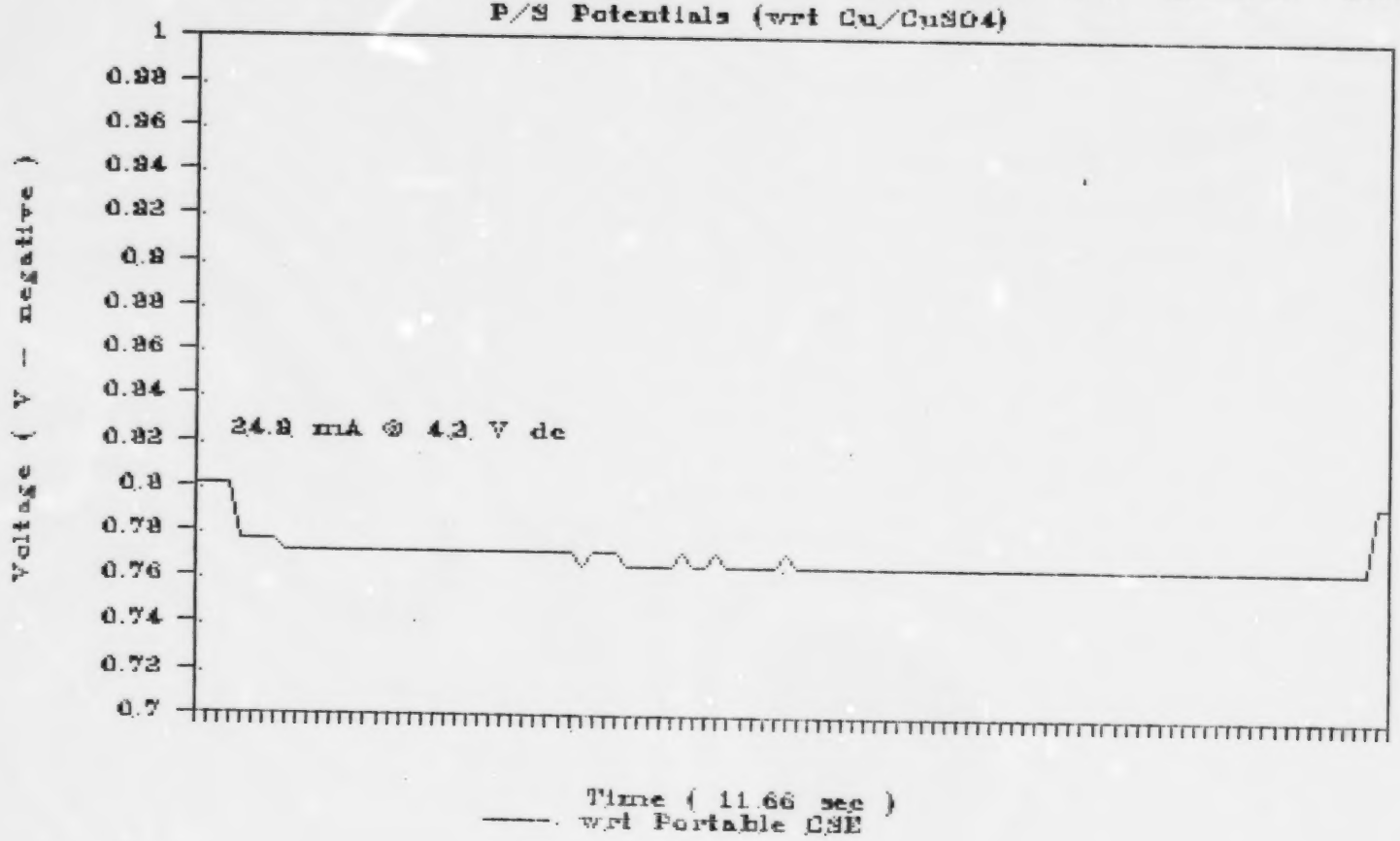

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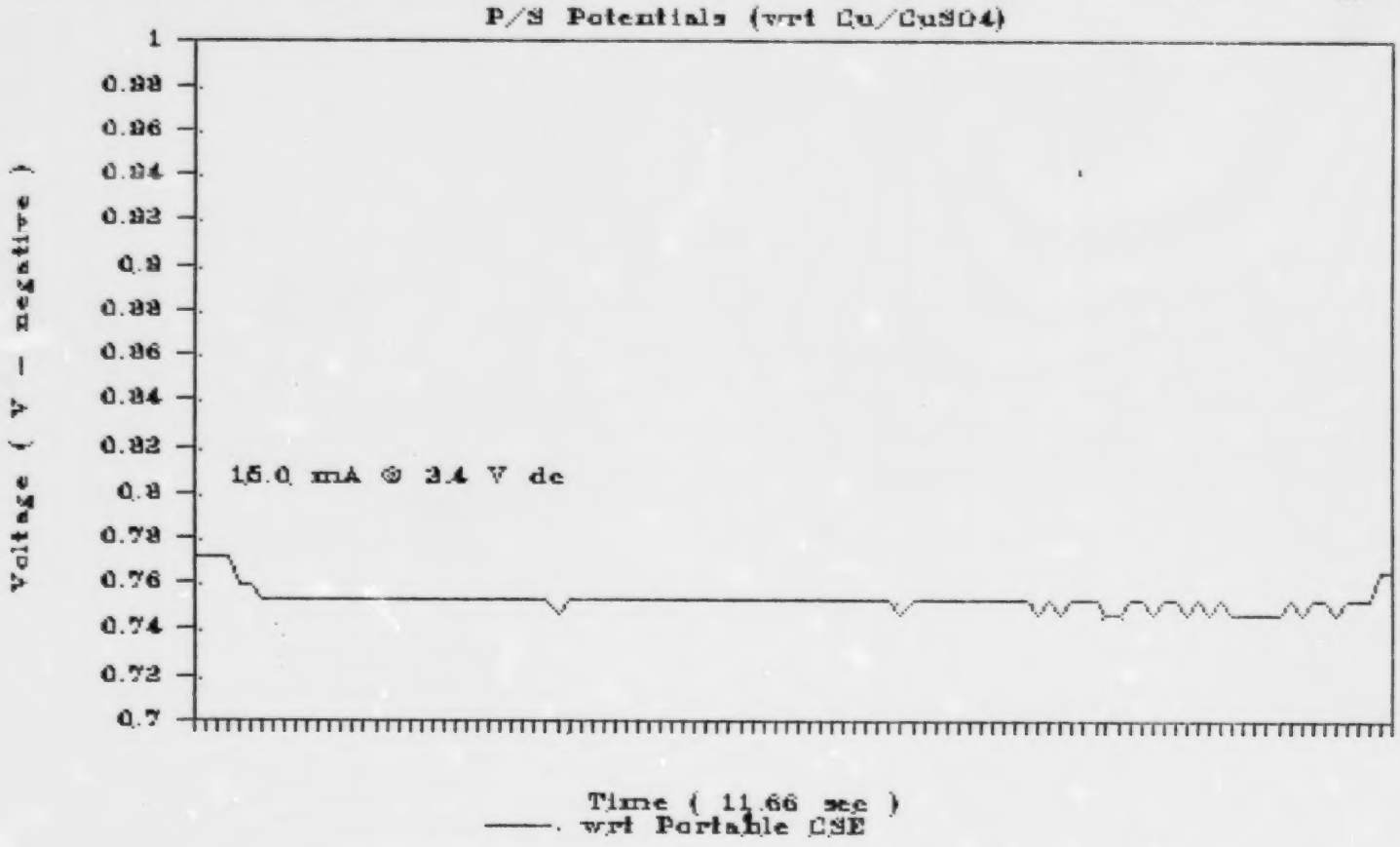

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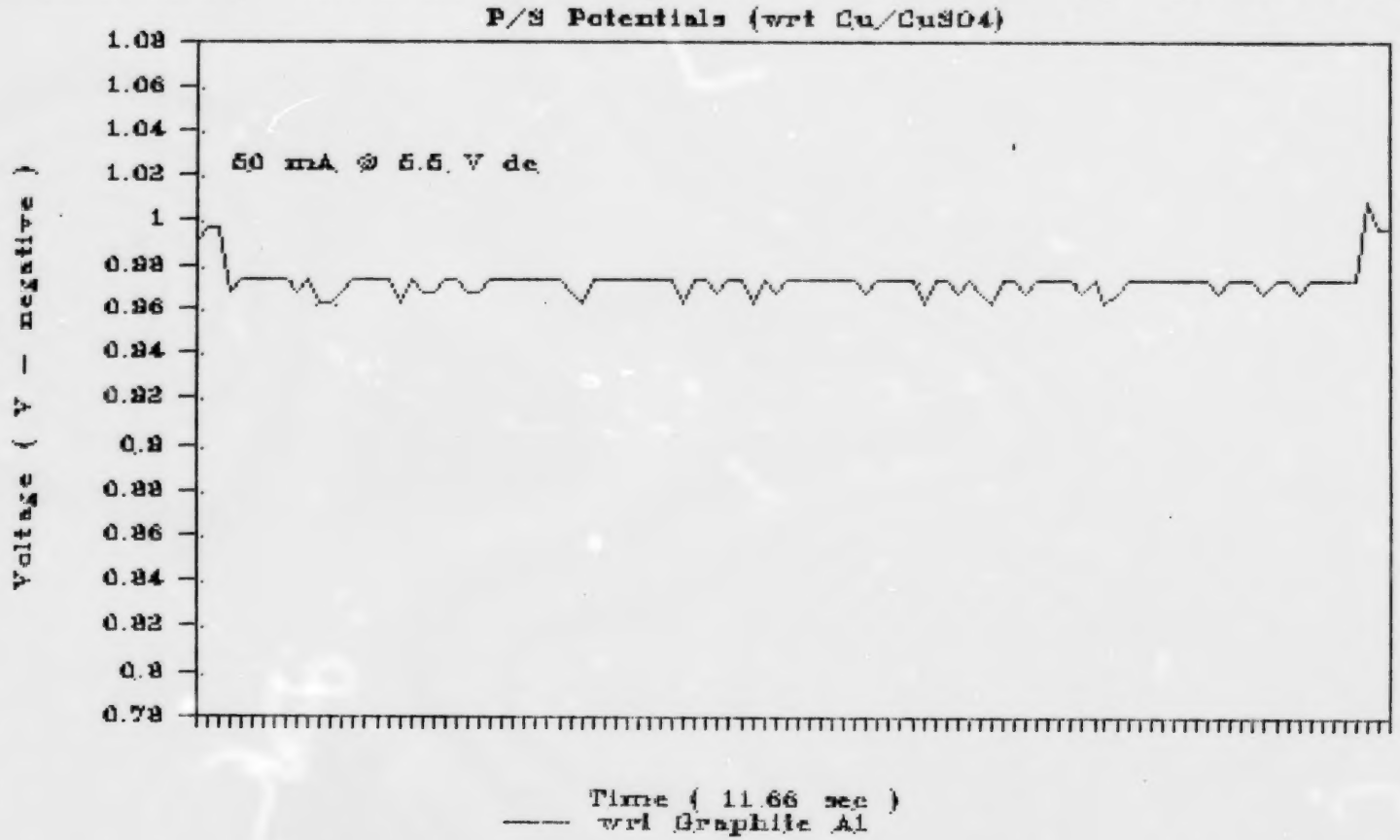

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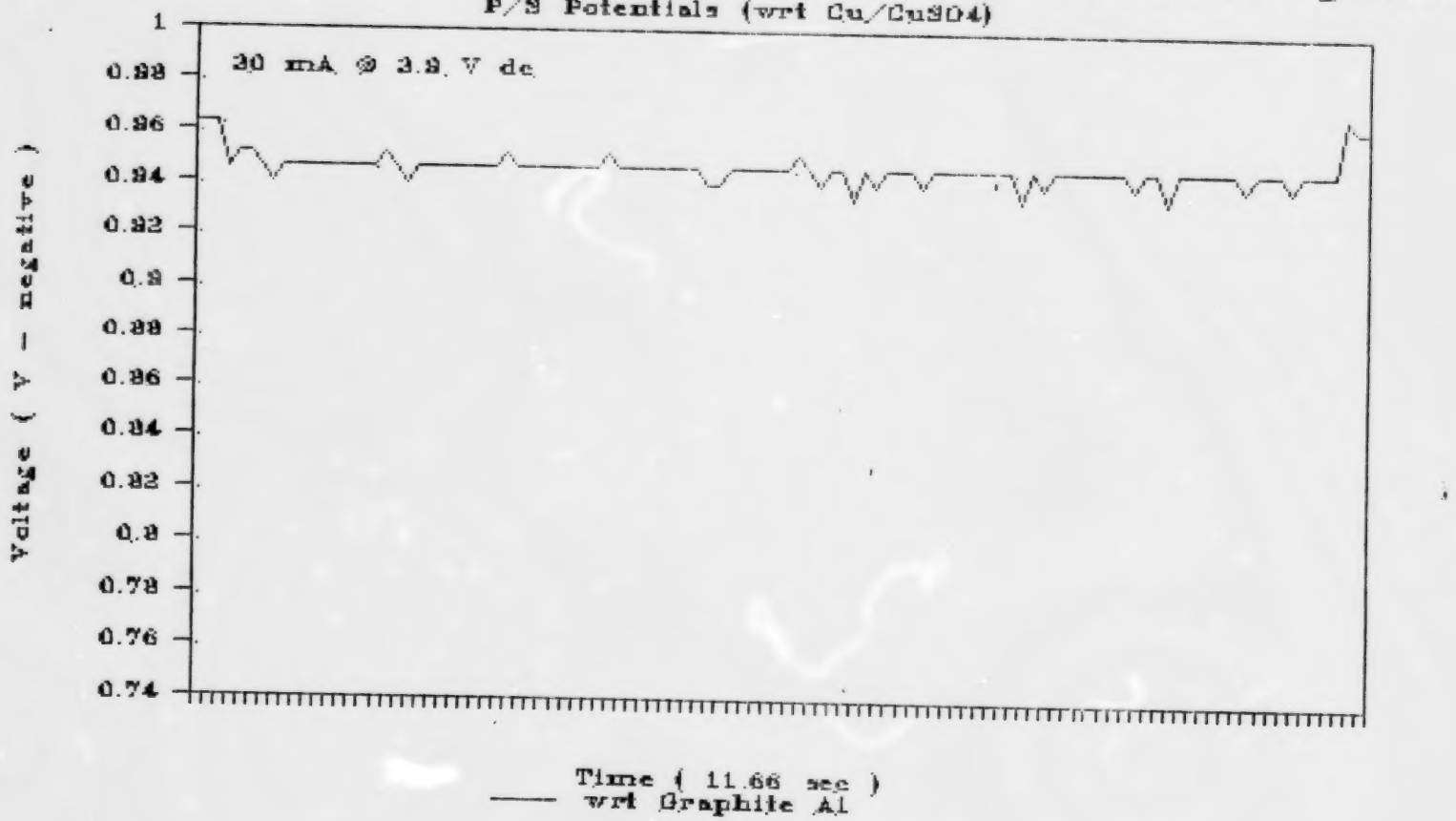

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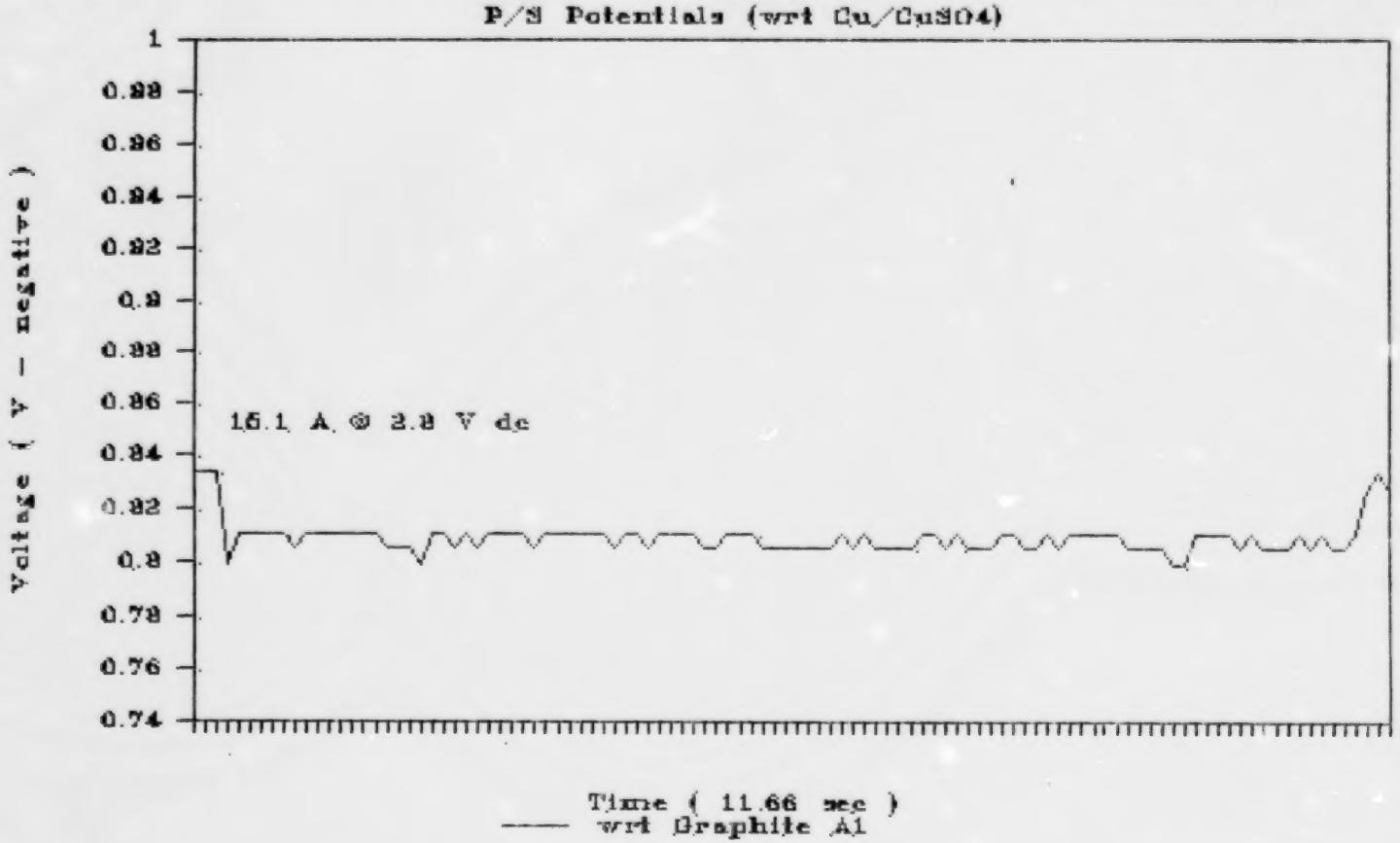

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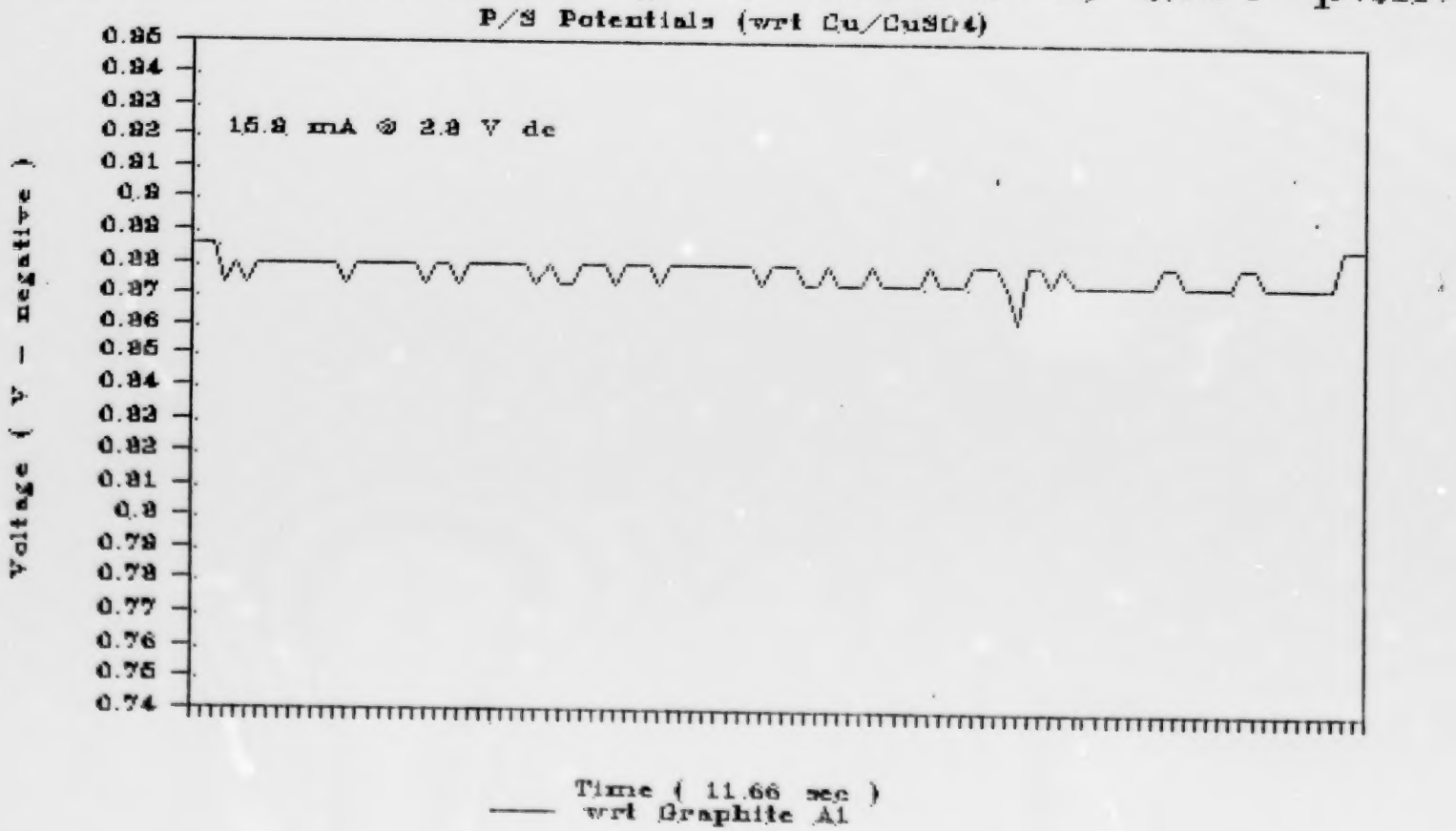

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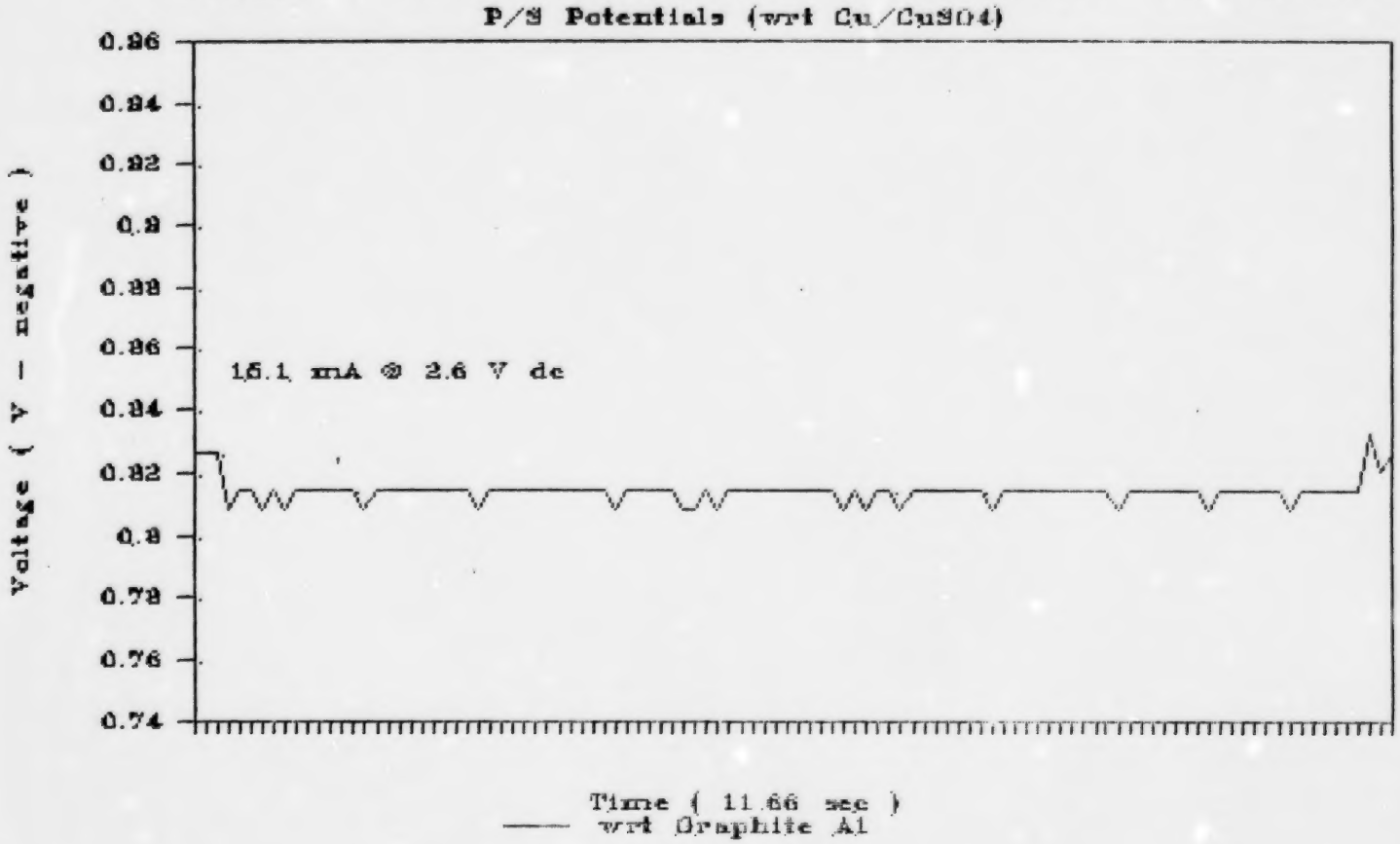

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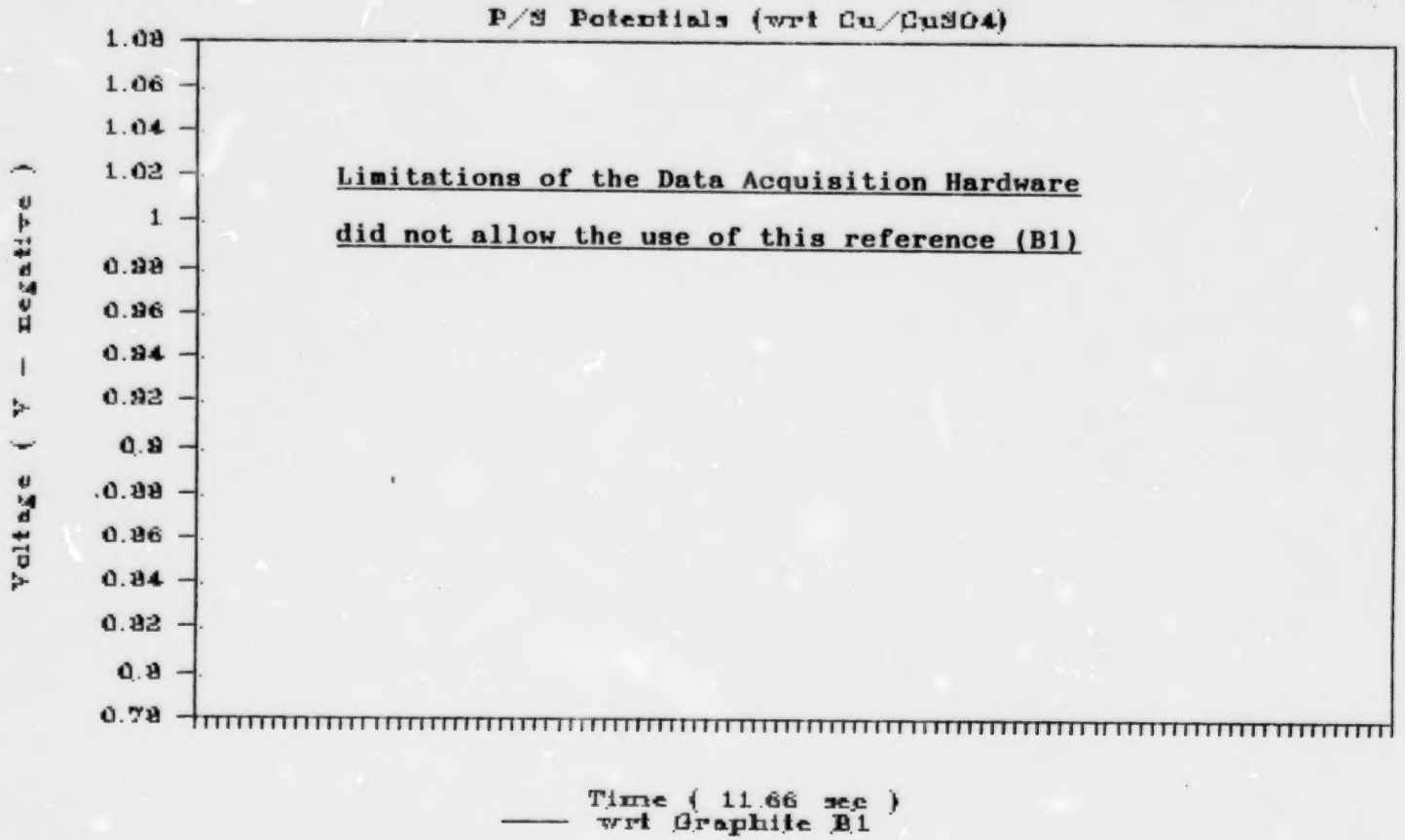

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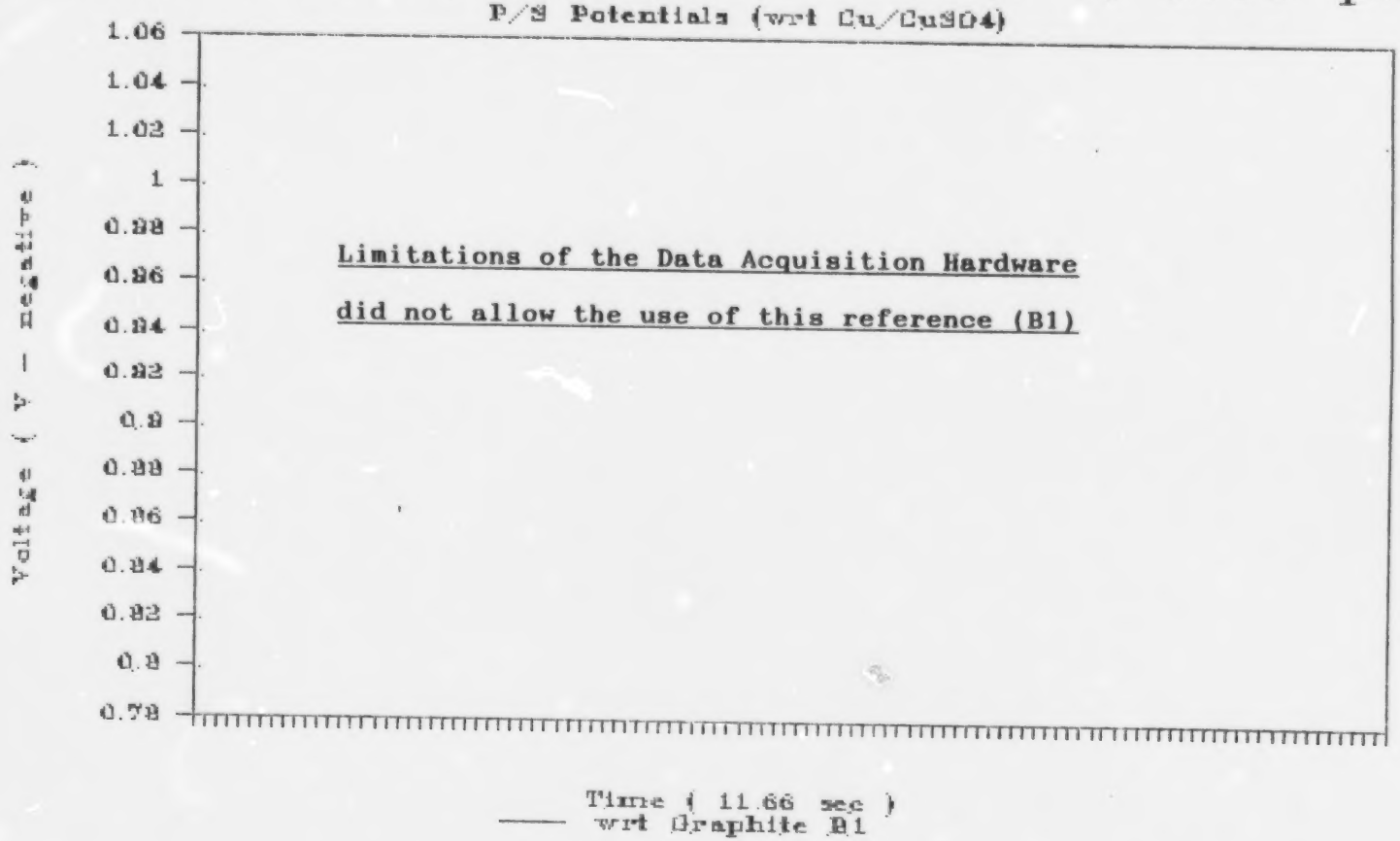

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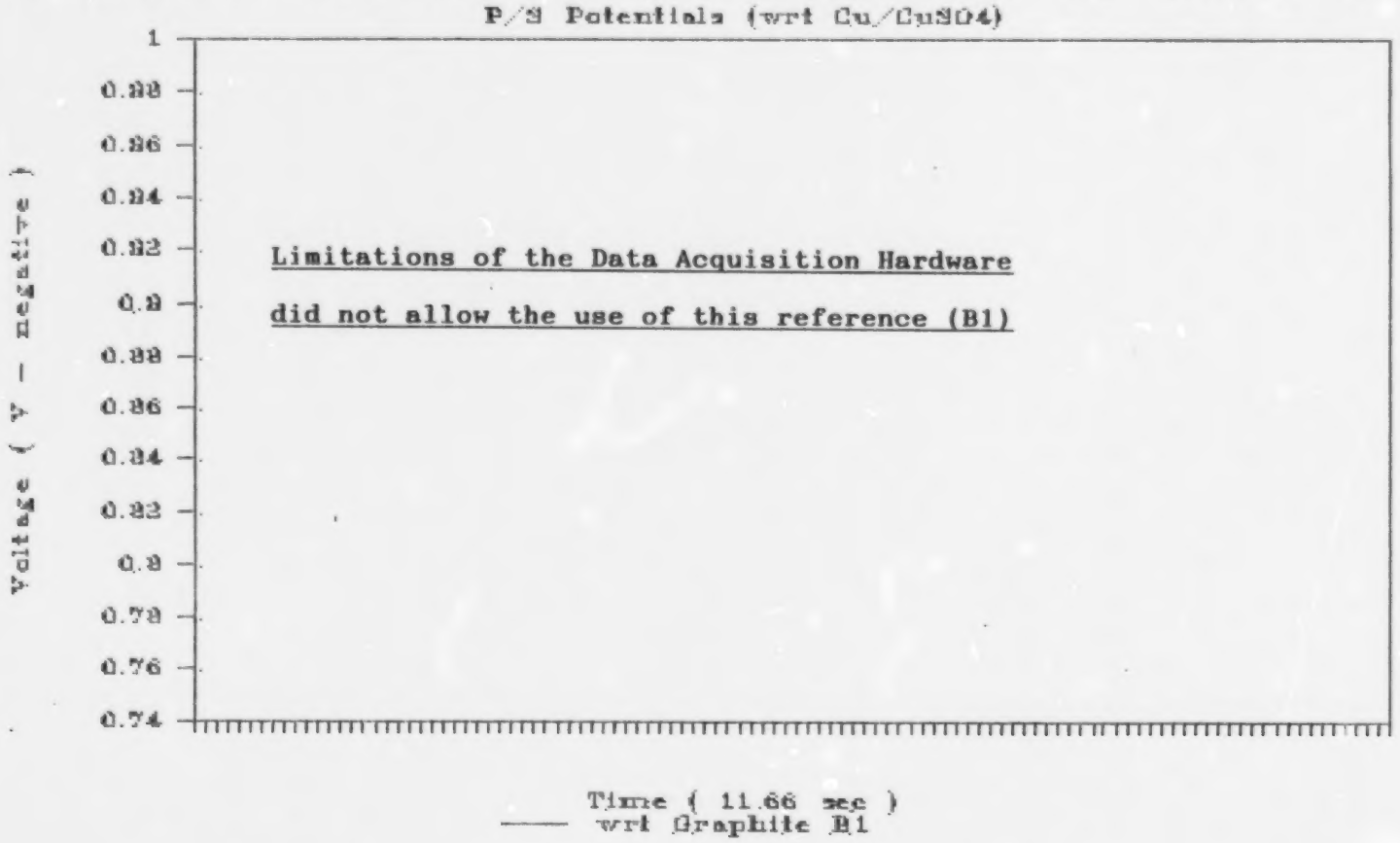

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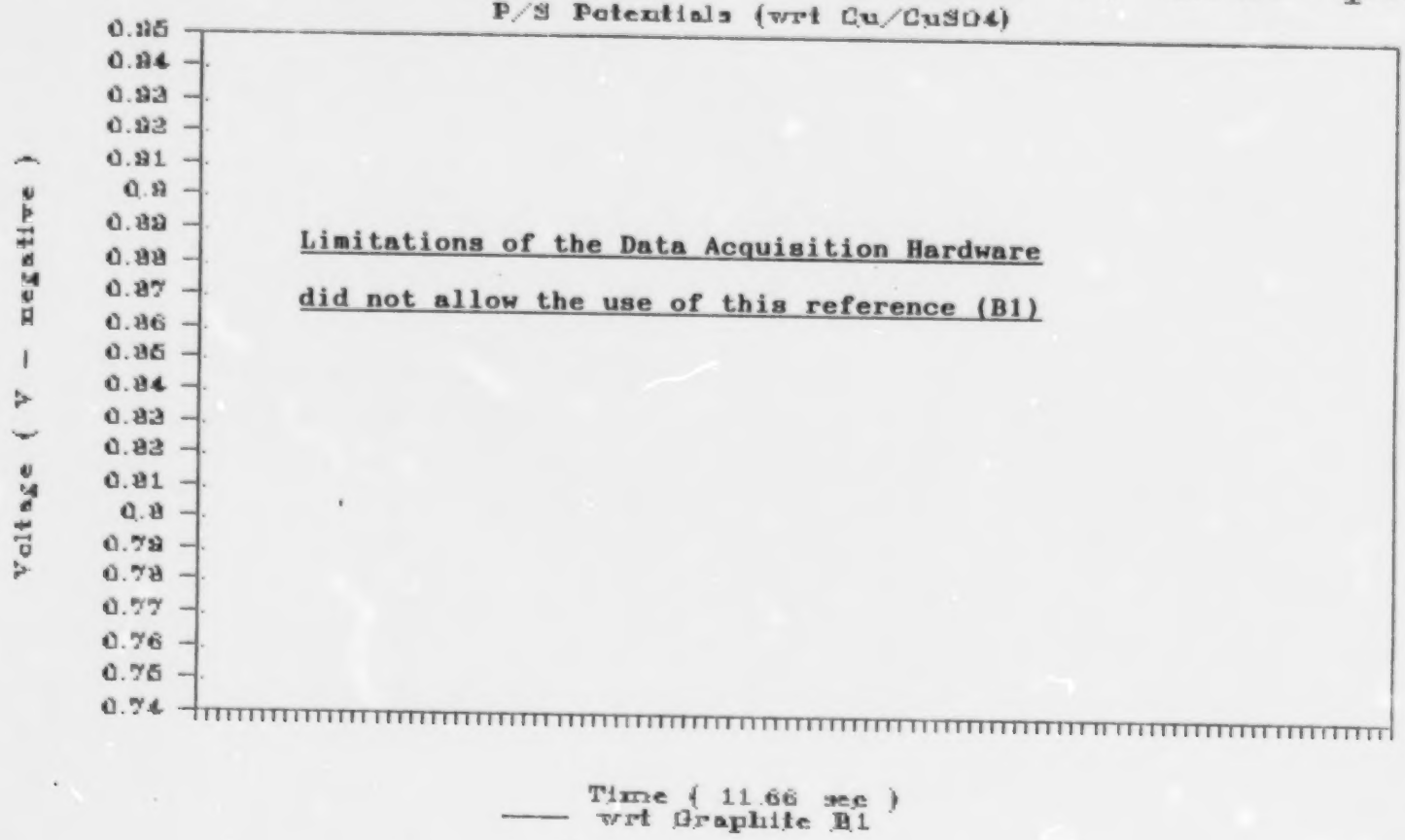

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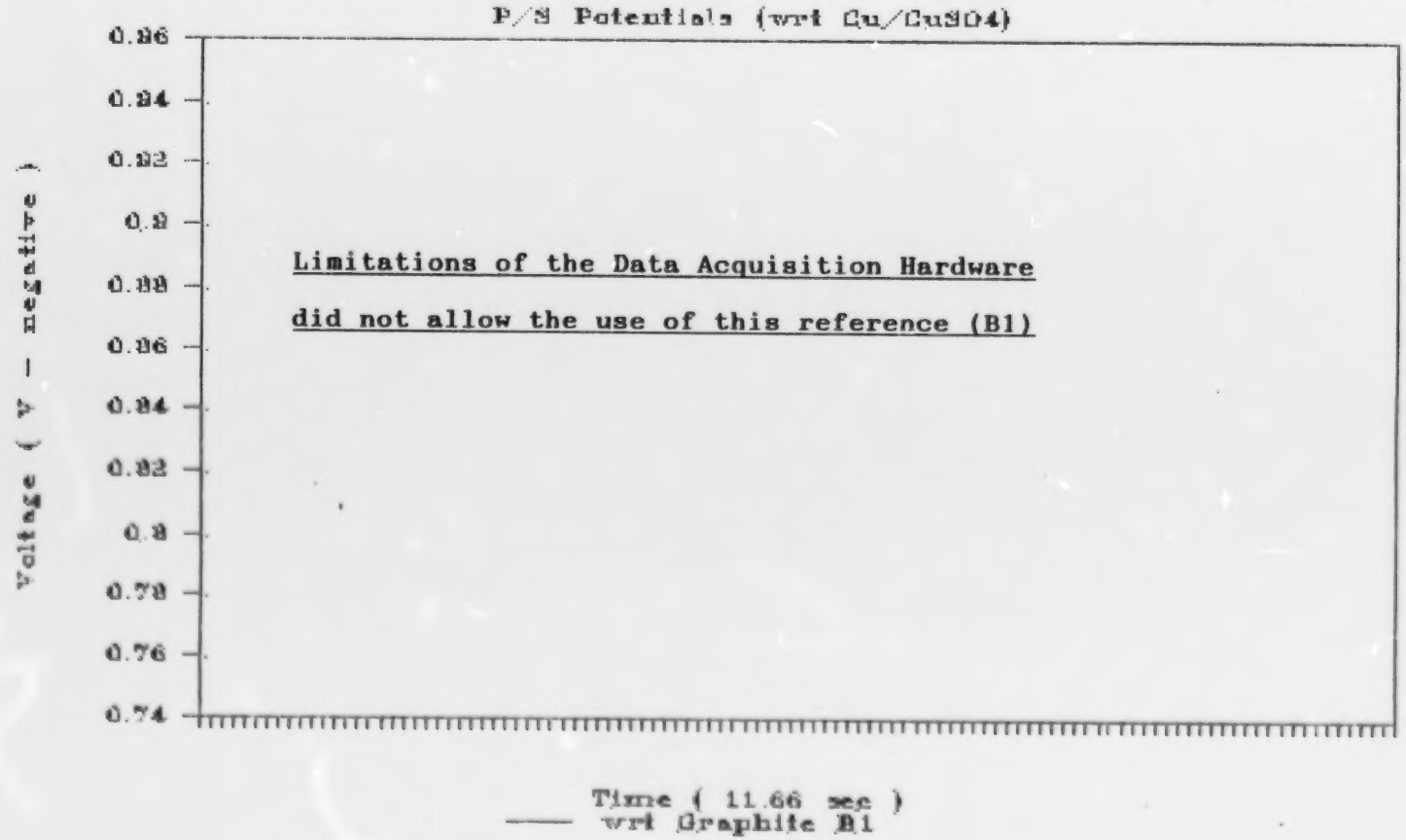

"Depolarization Curves - Graphite Reference A2"

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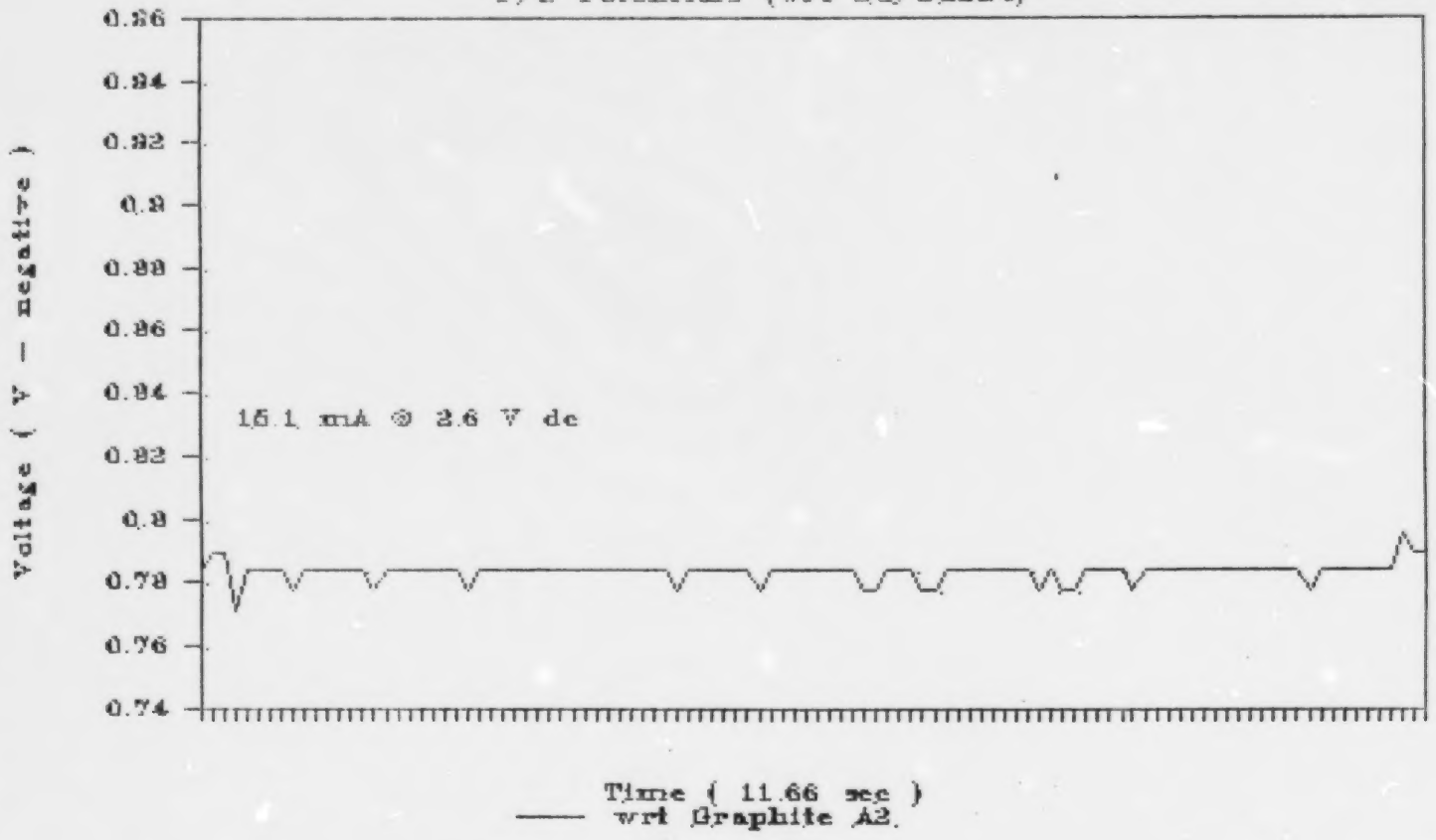

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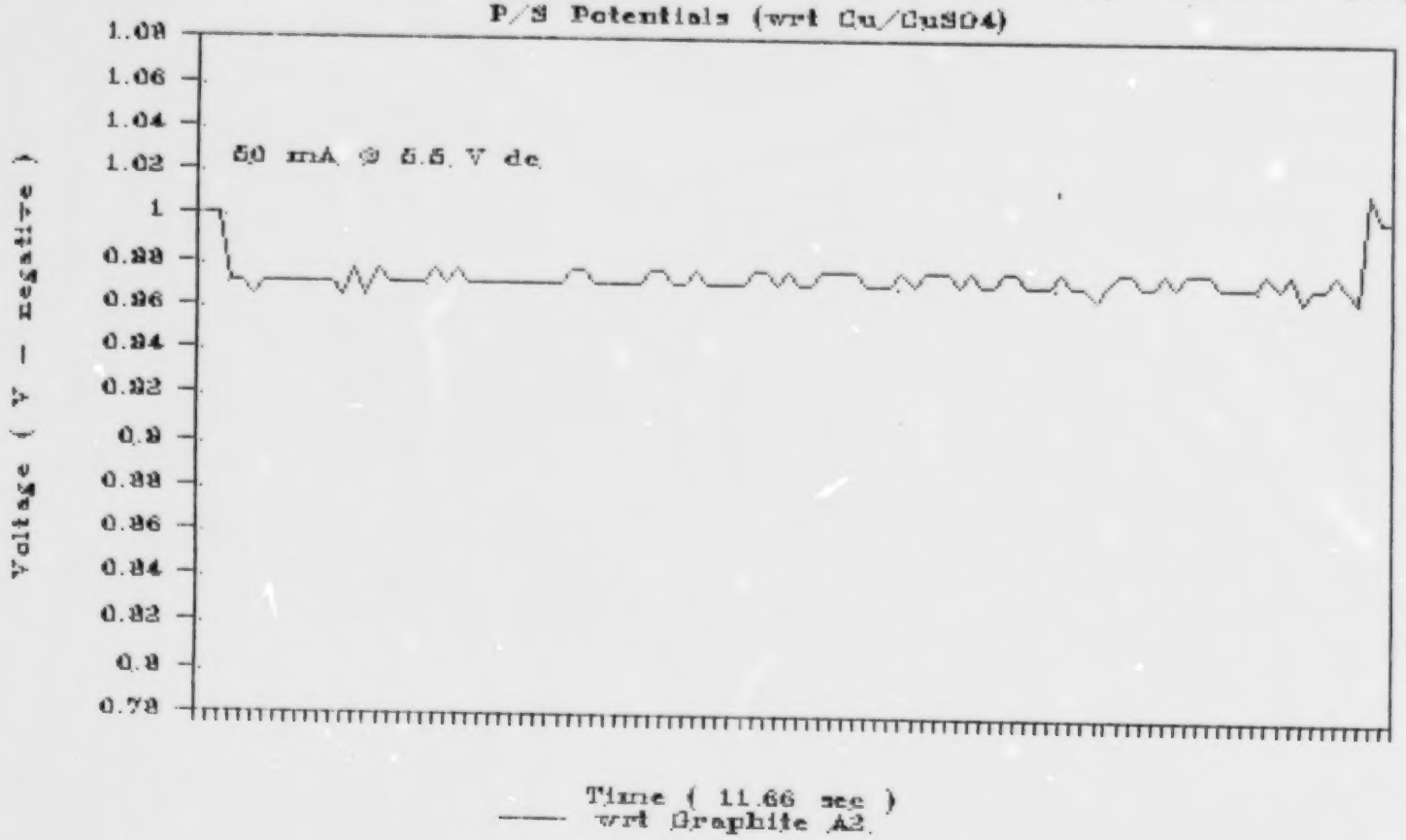

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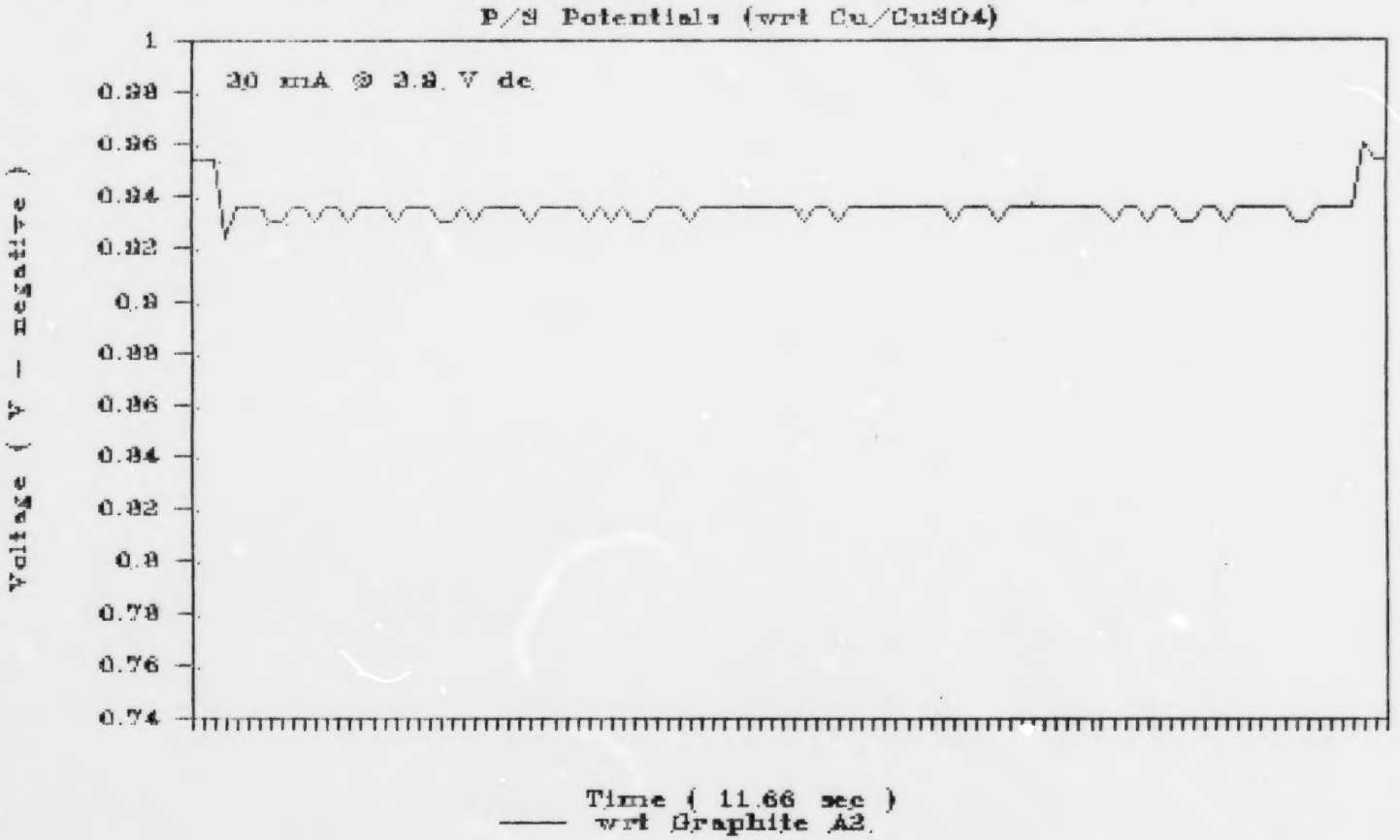

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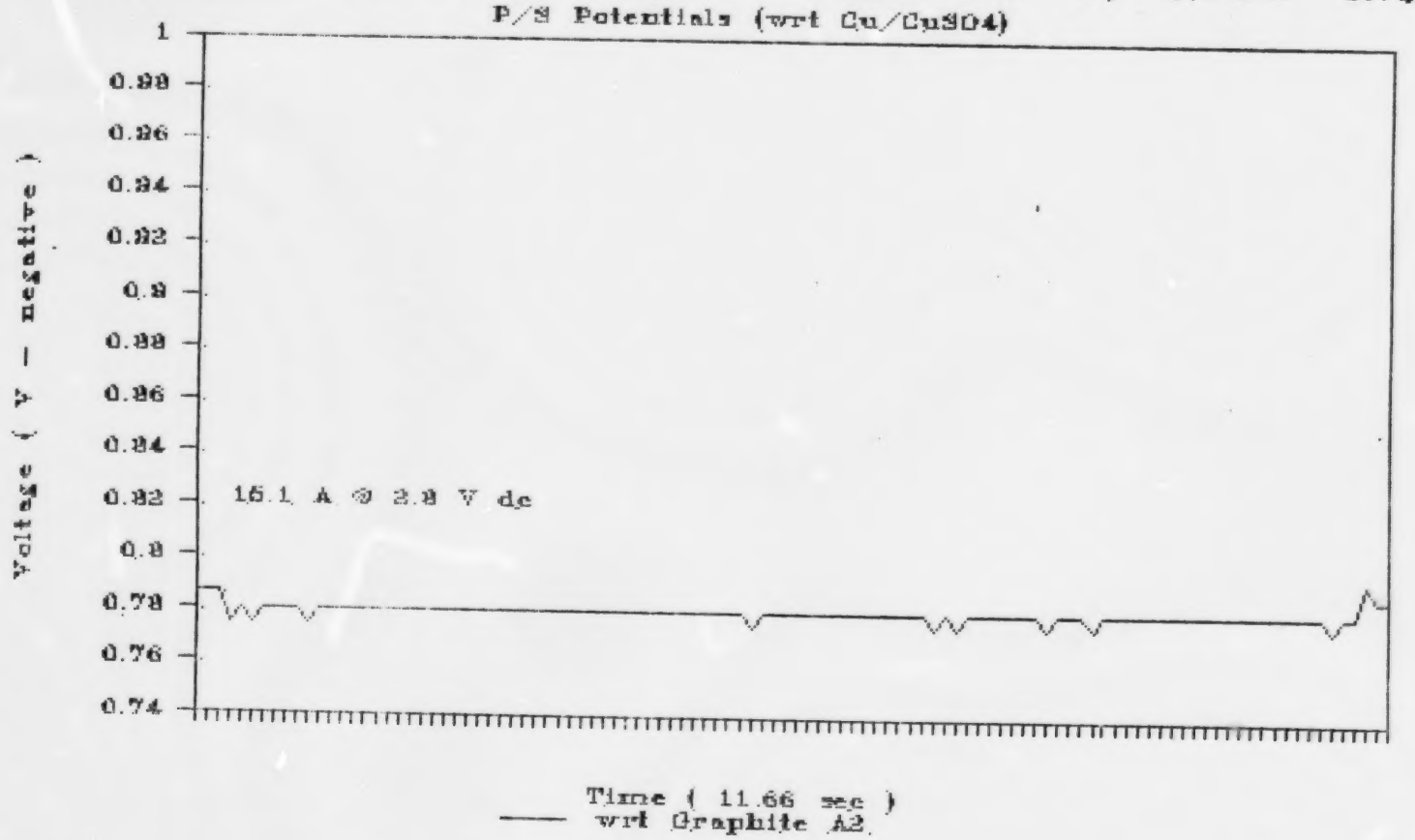

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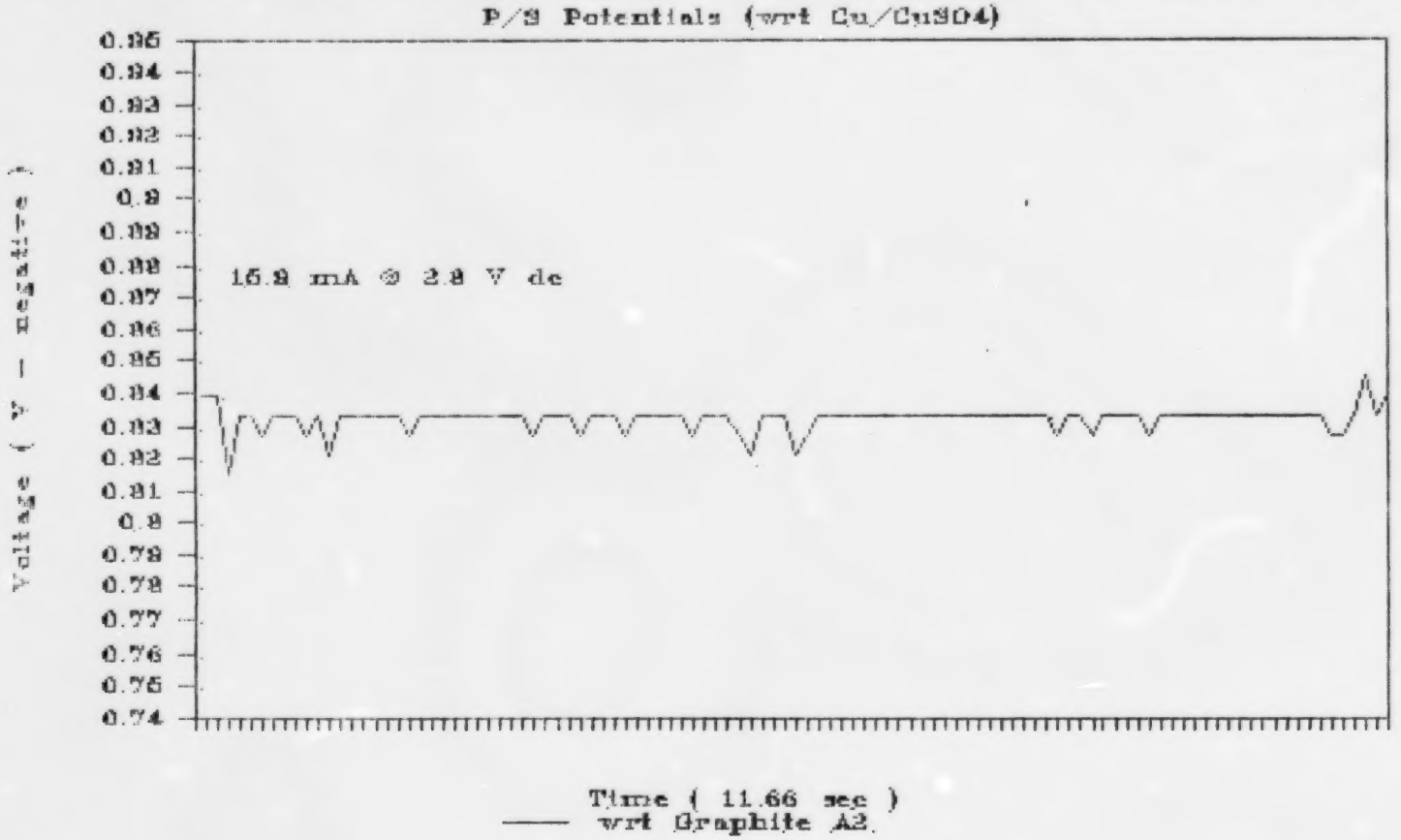

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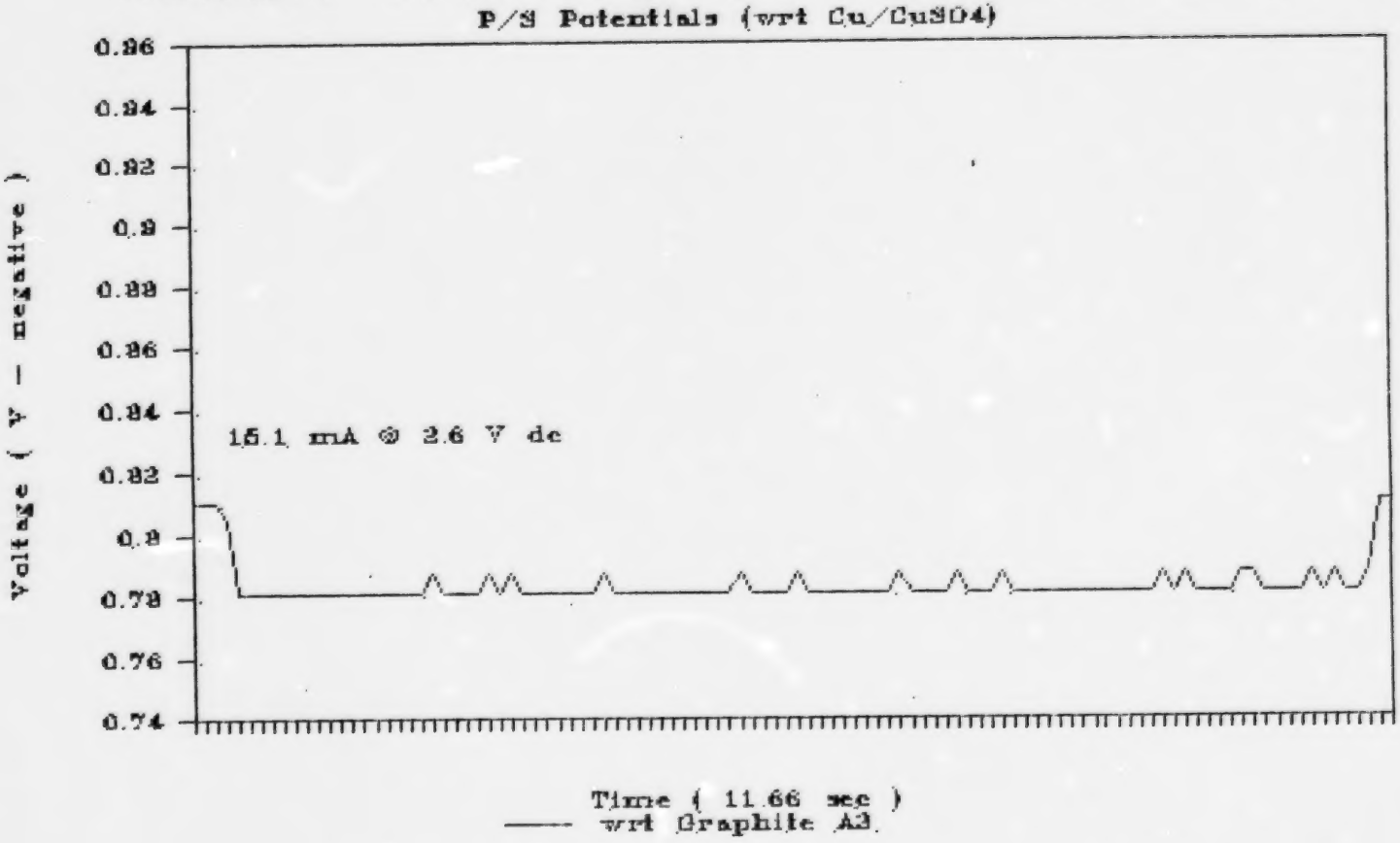

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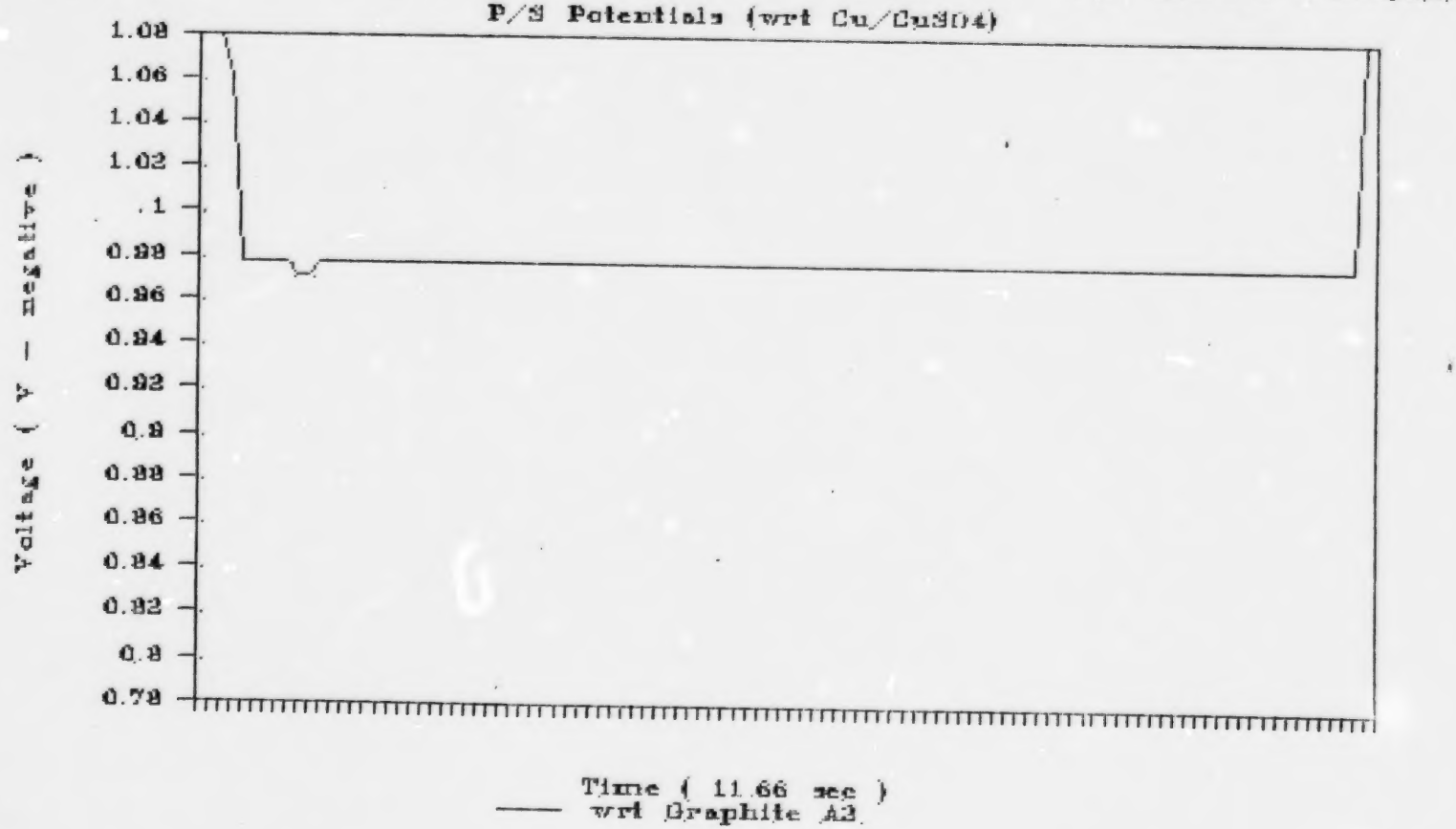

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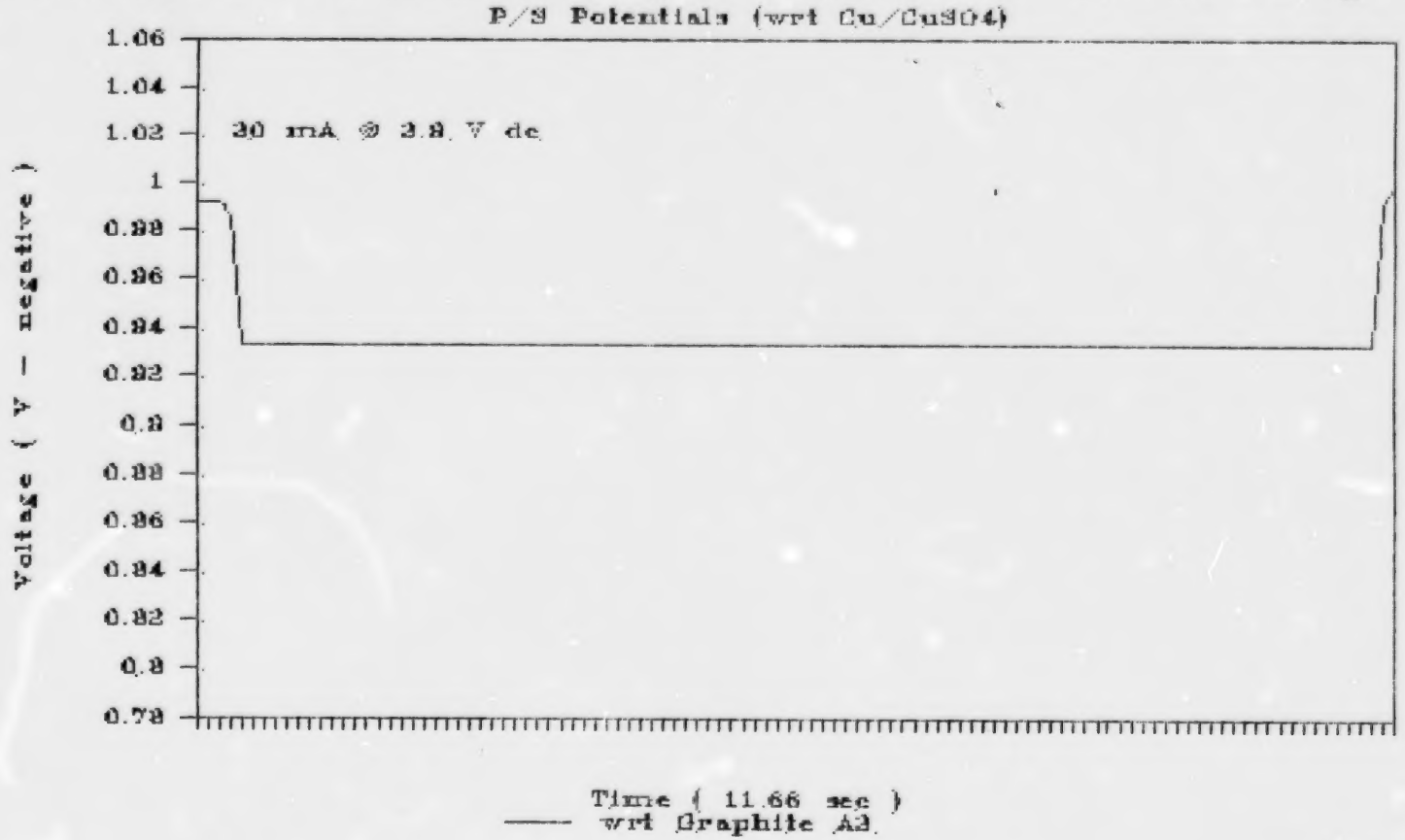

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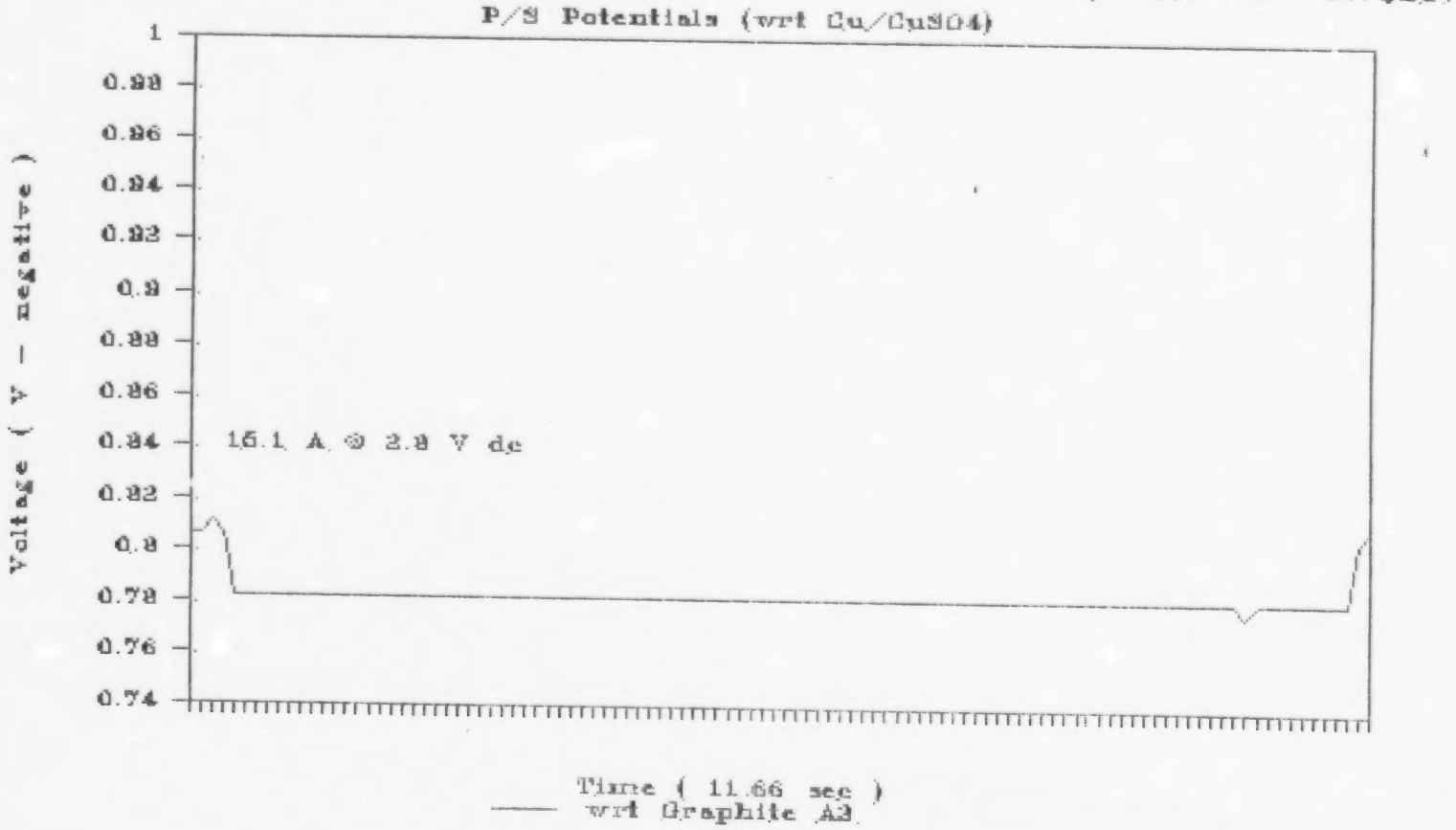

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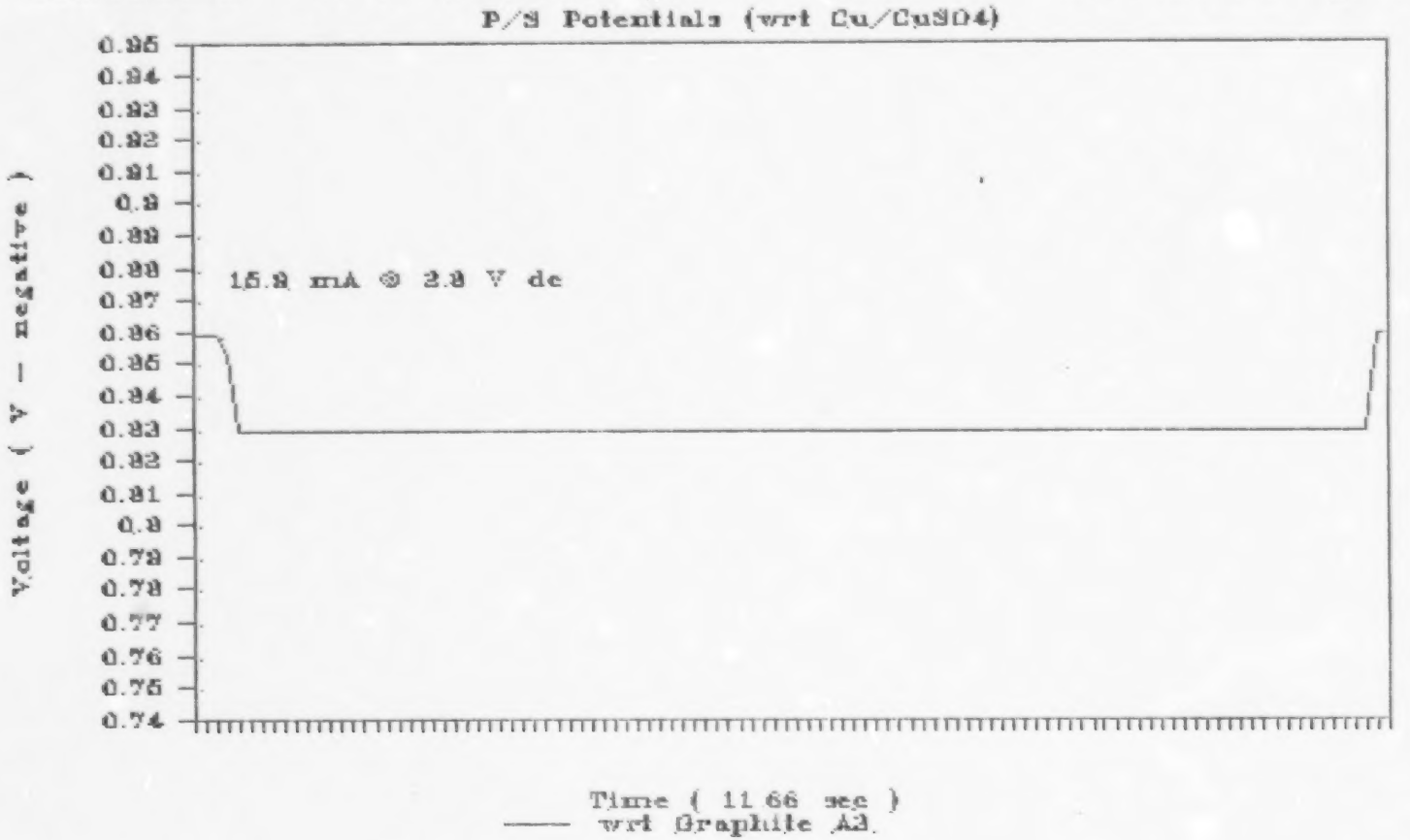

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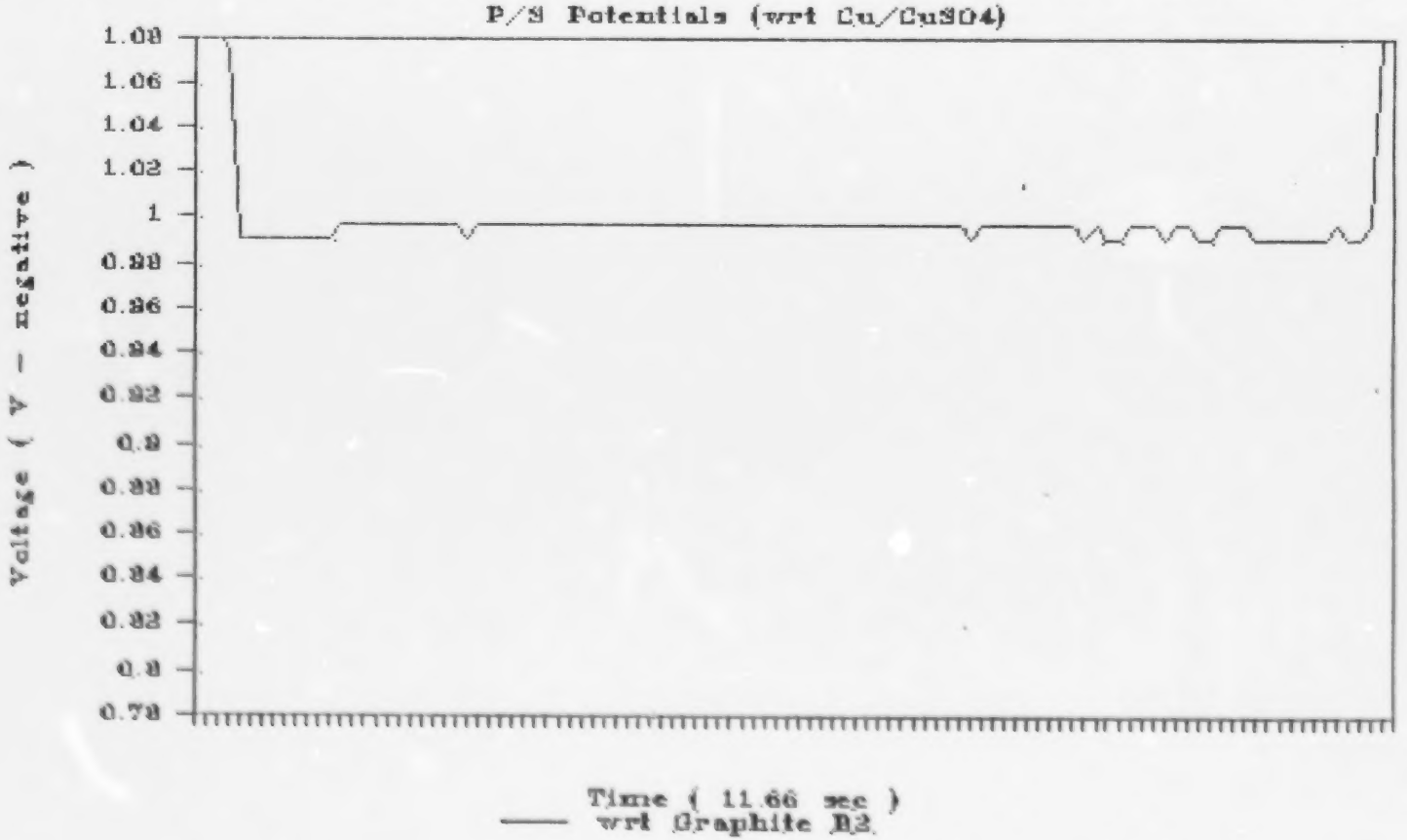

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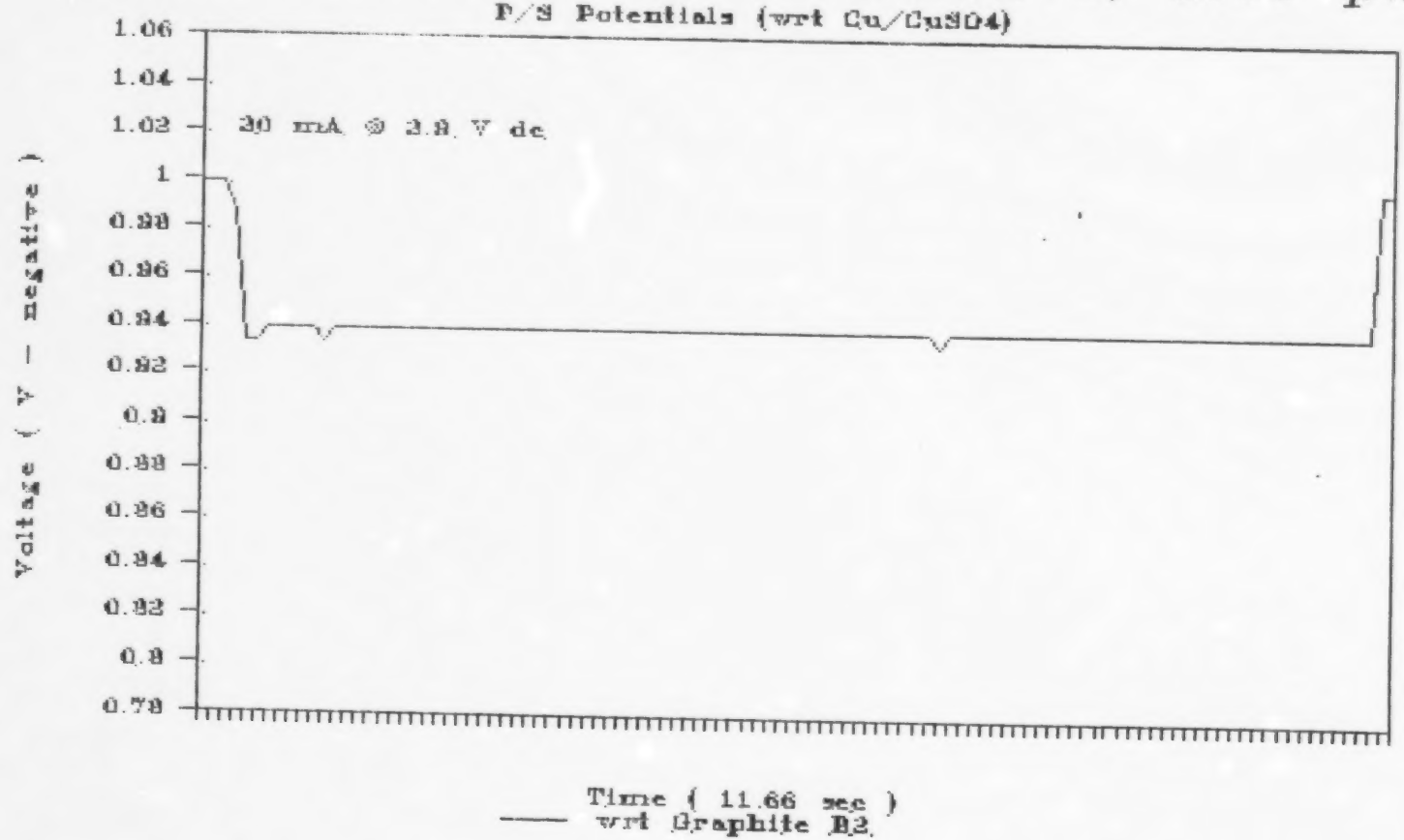

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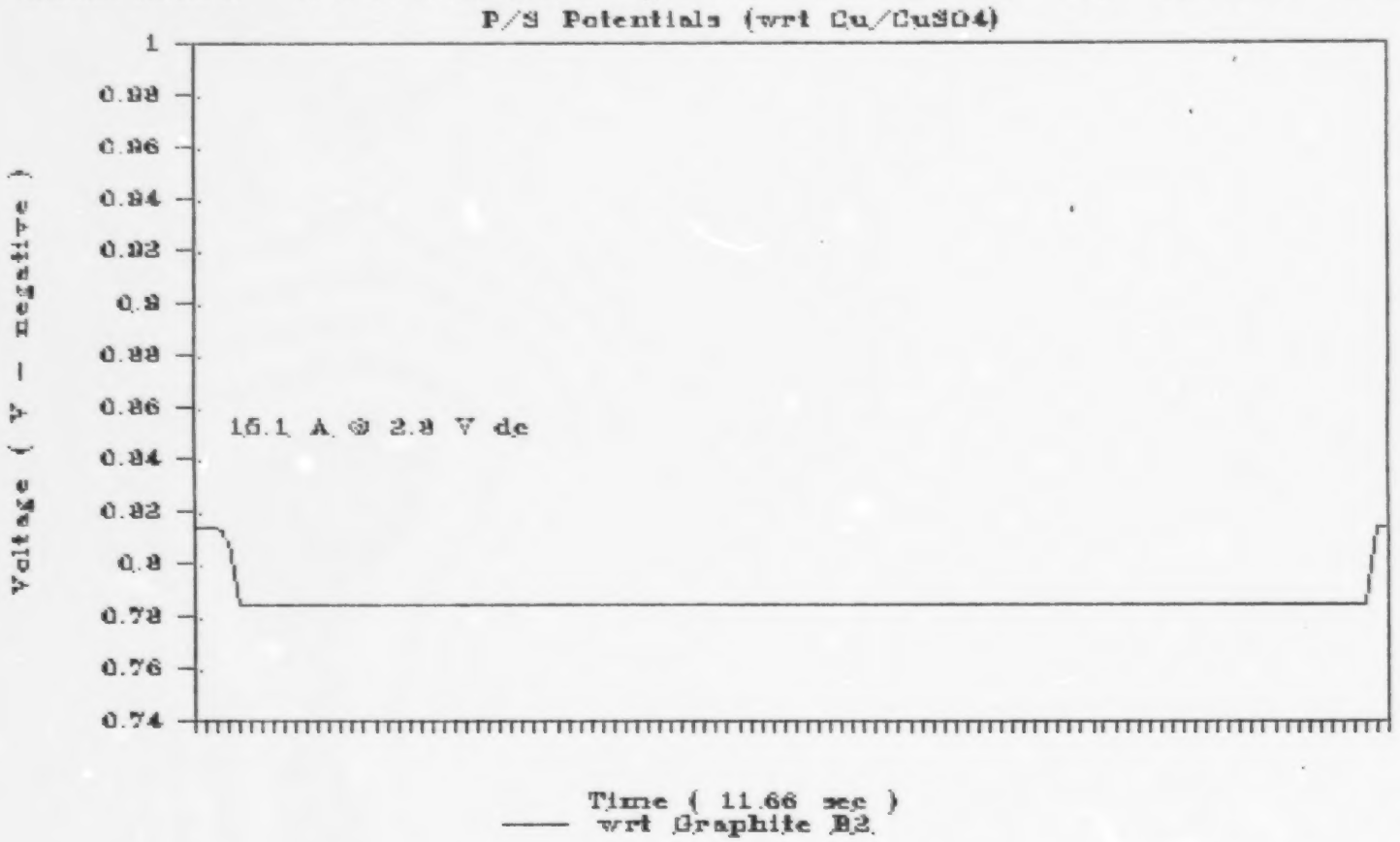

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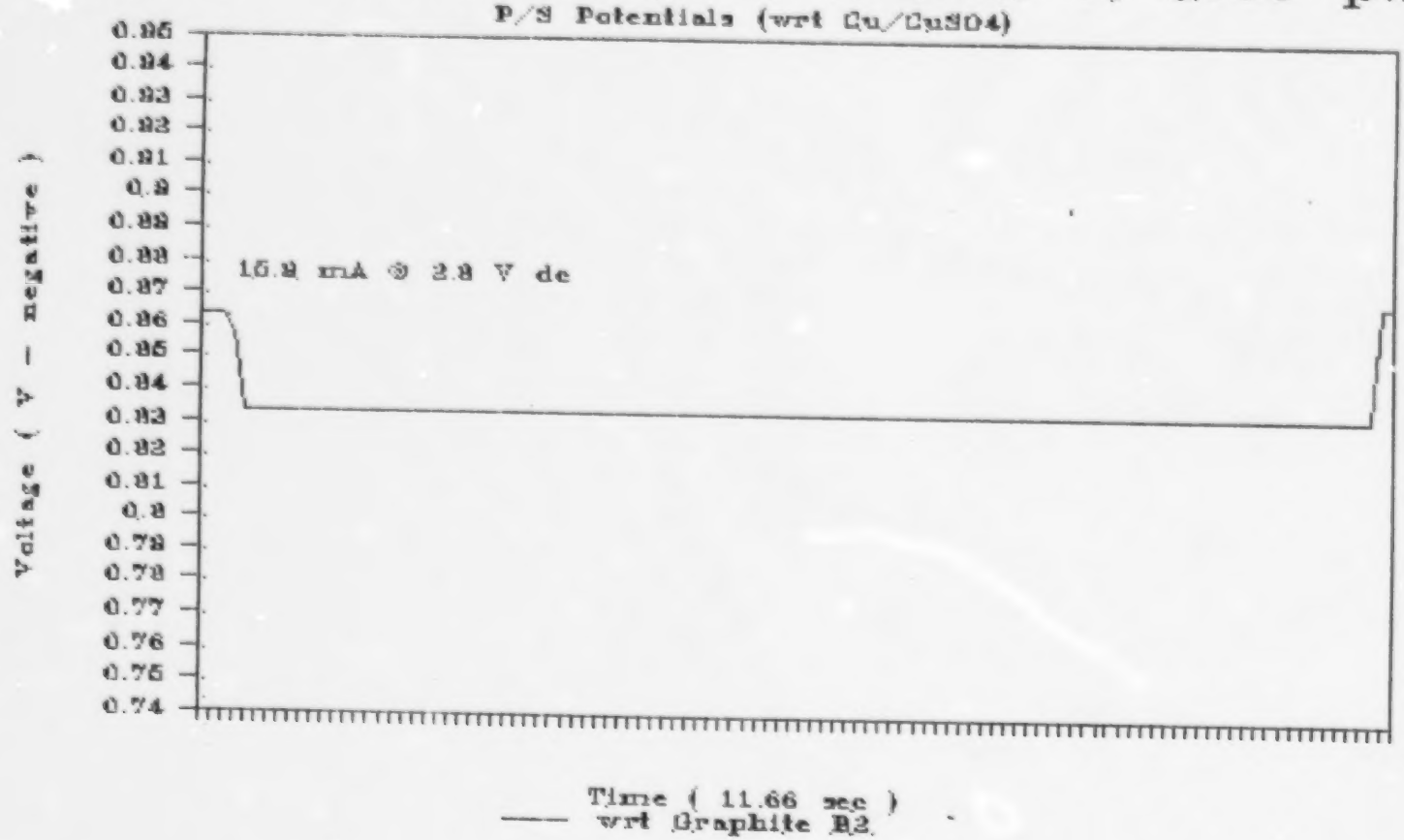

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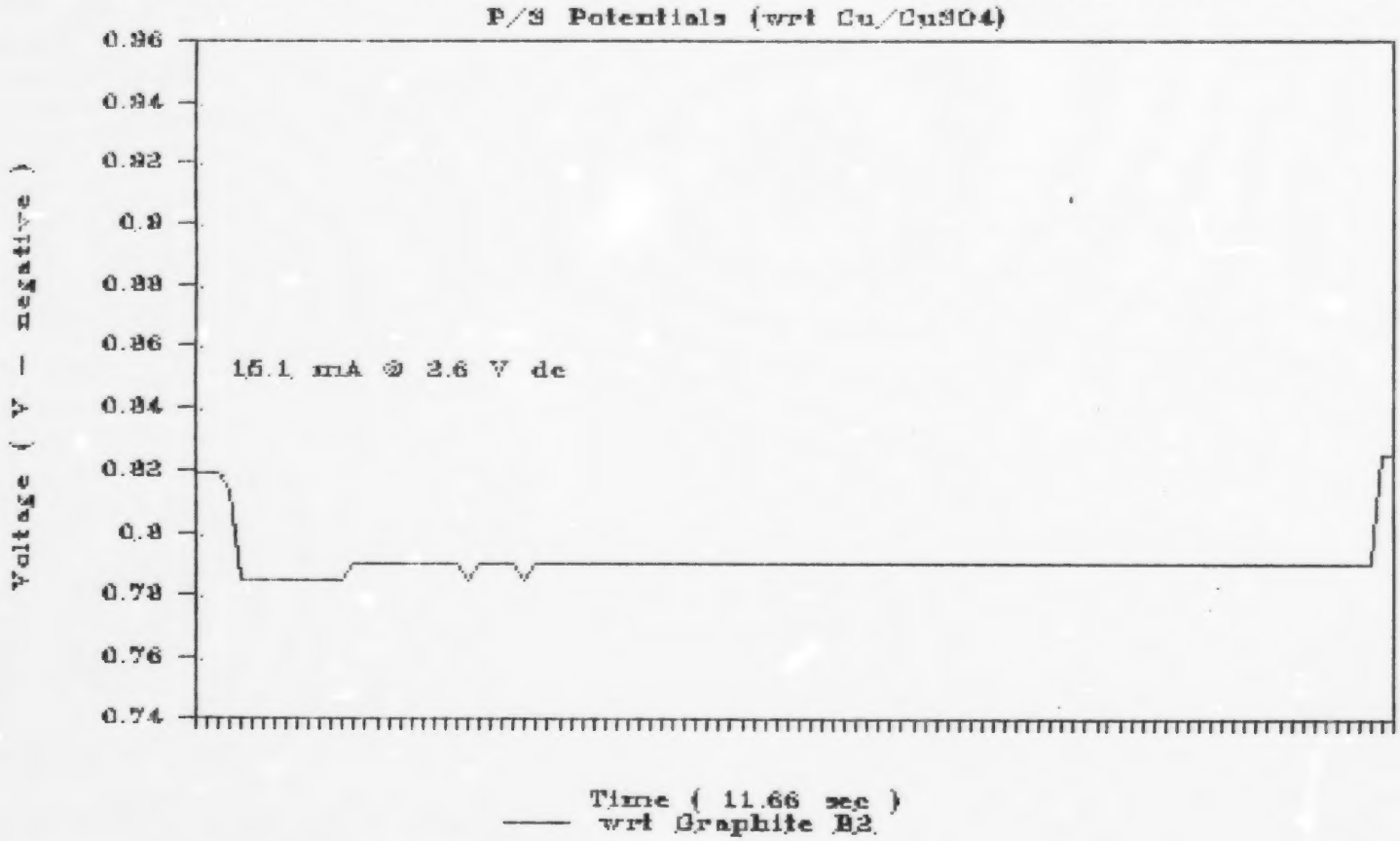

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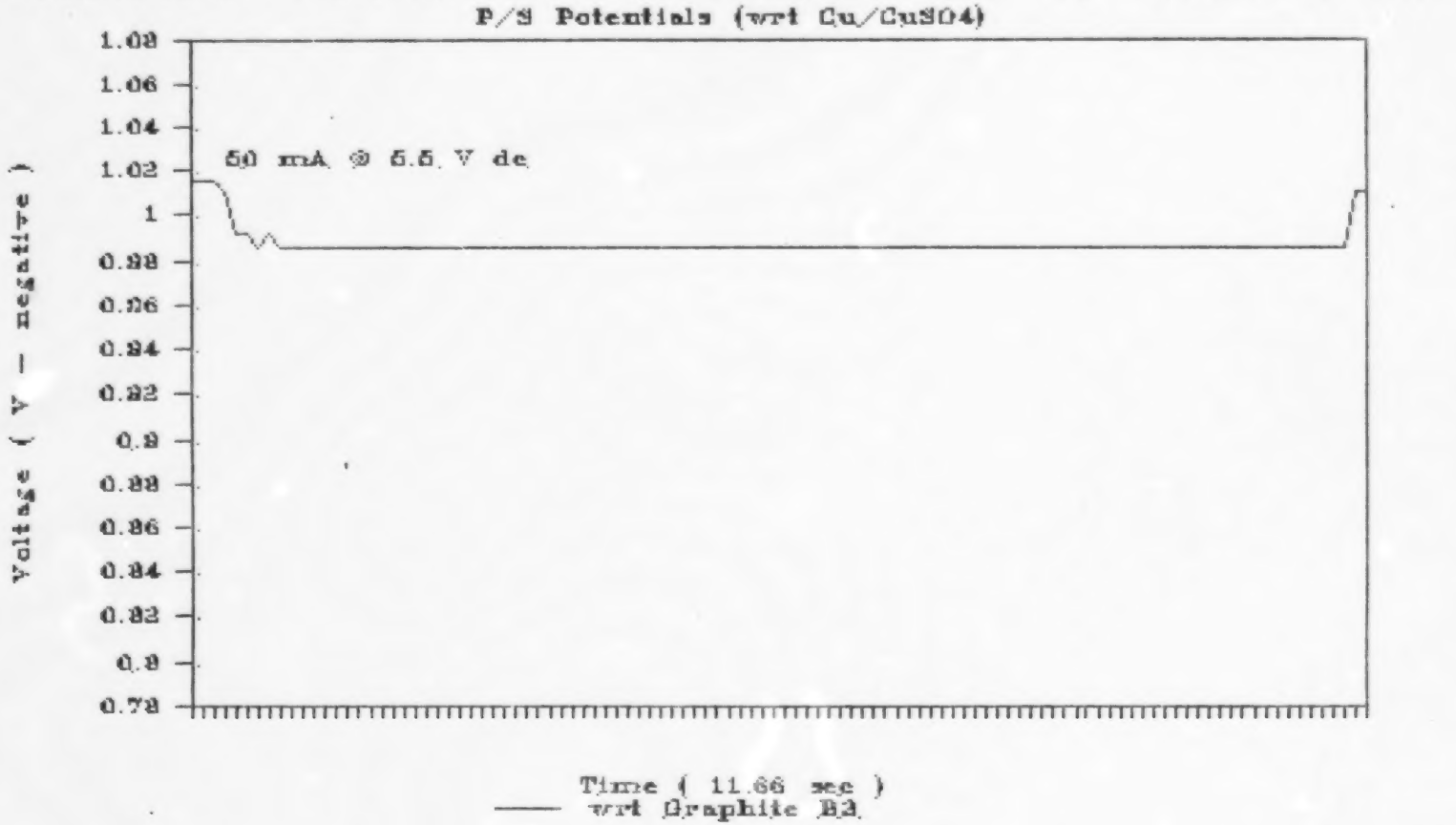

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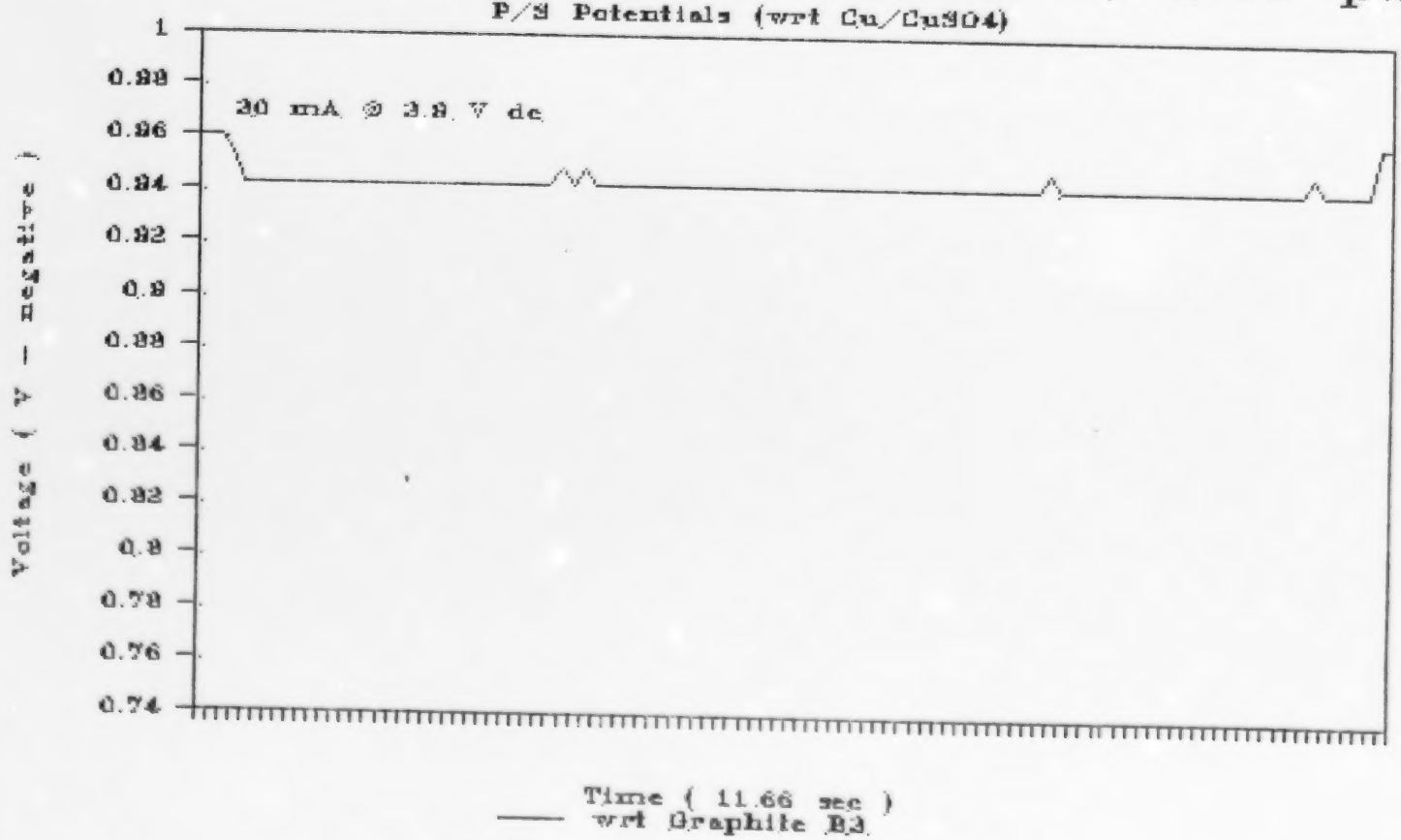

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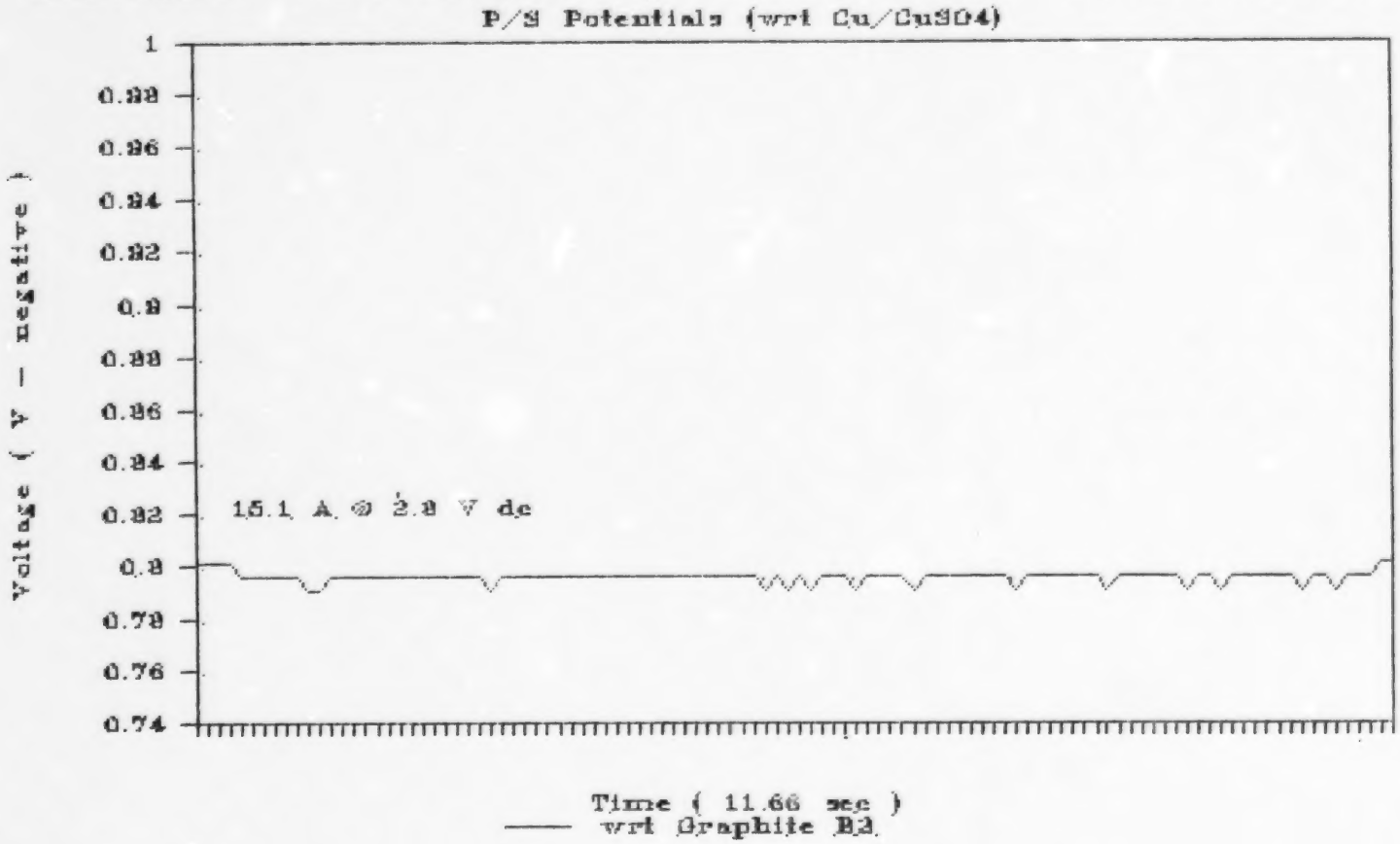

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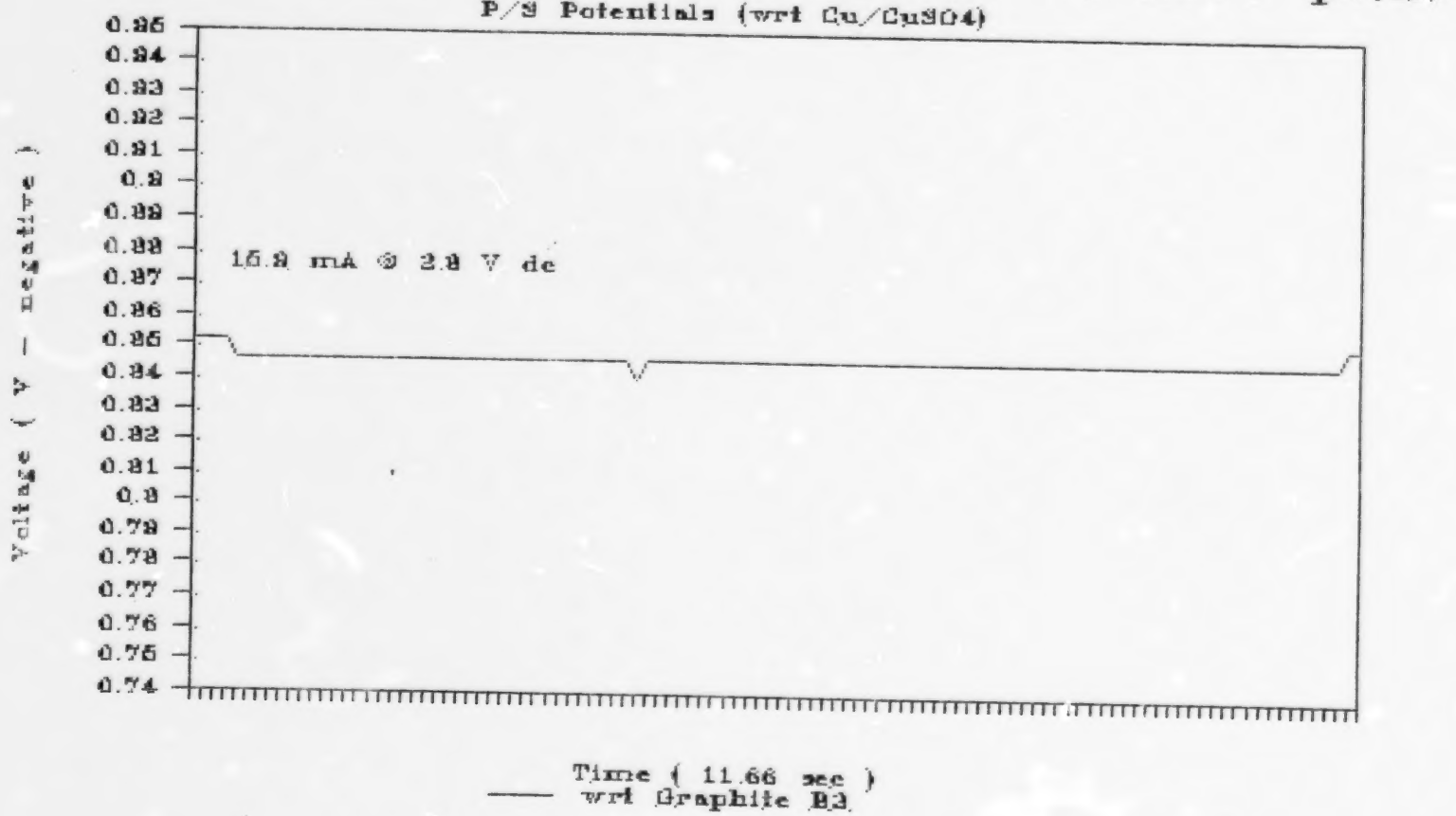

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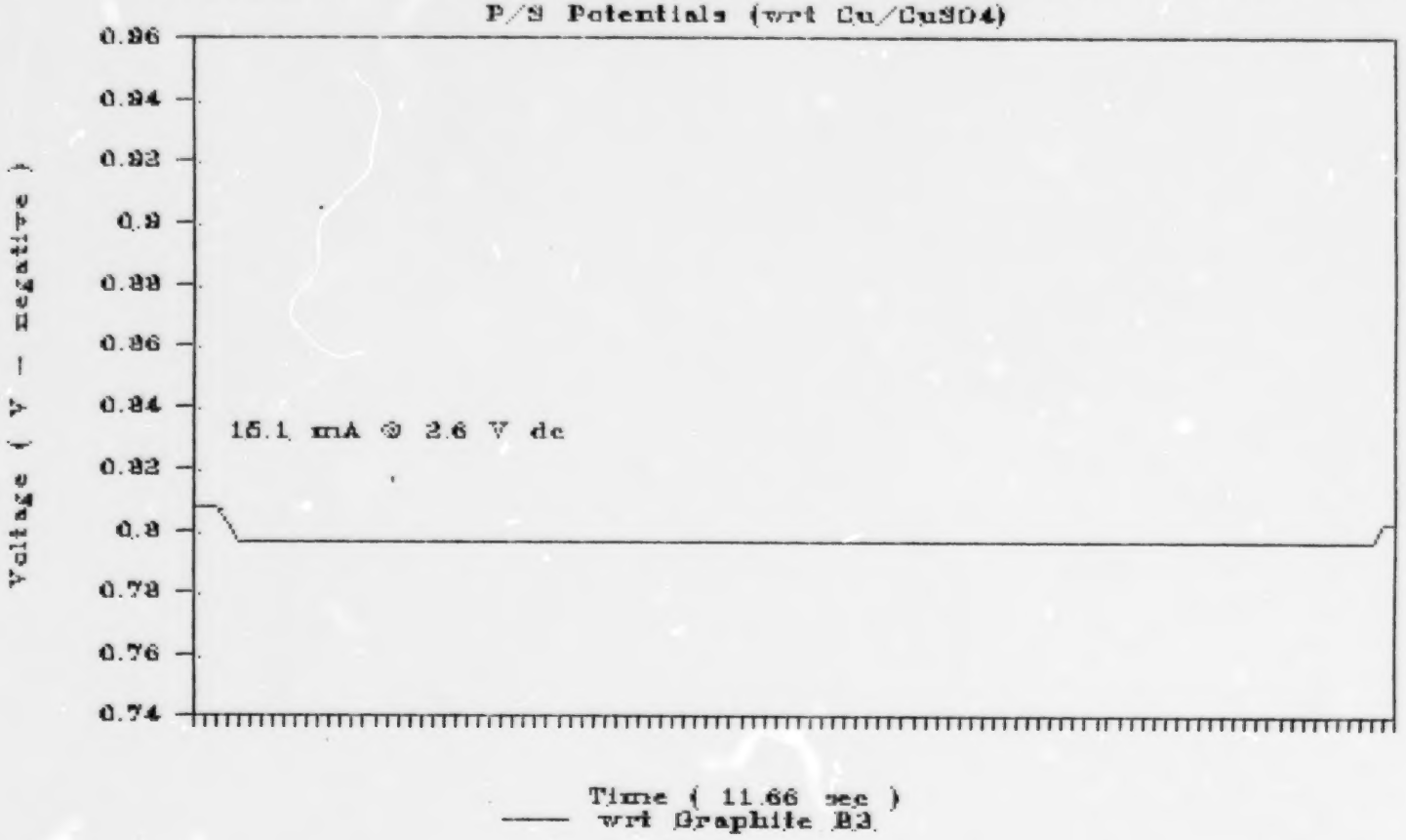

"Depolarization Curves: Portable CSE"

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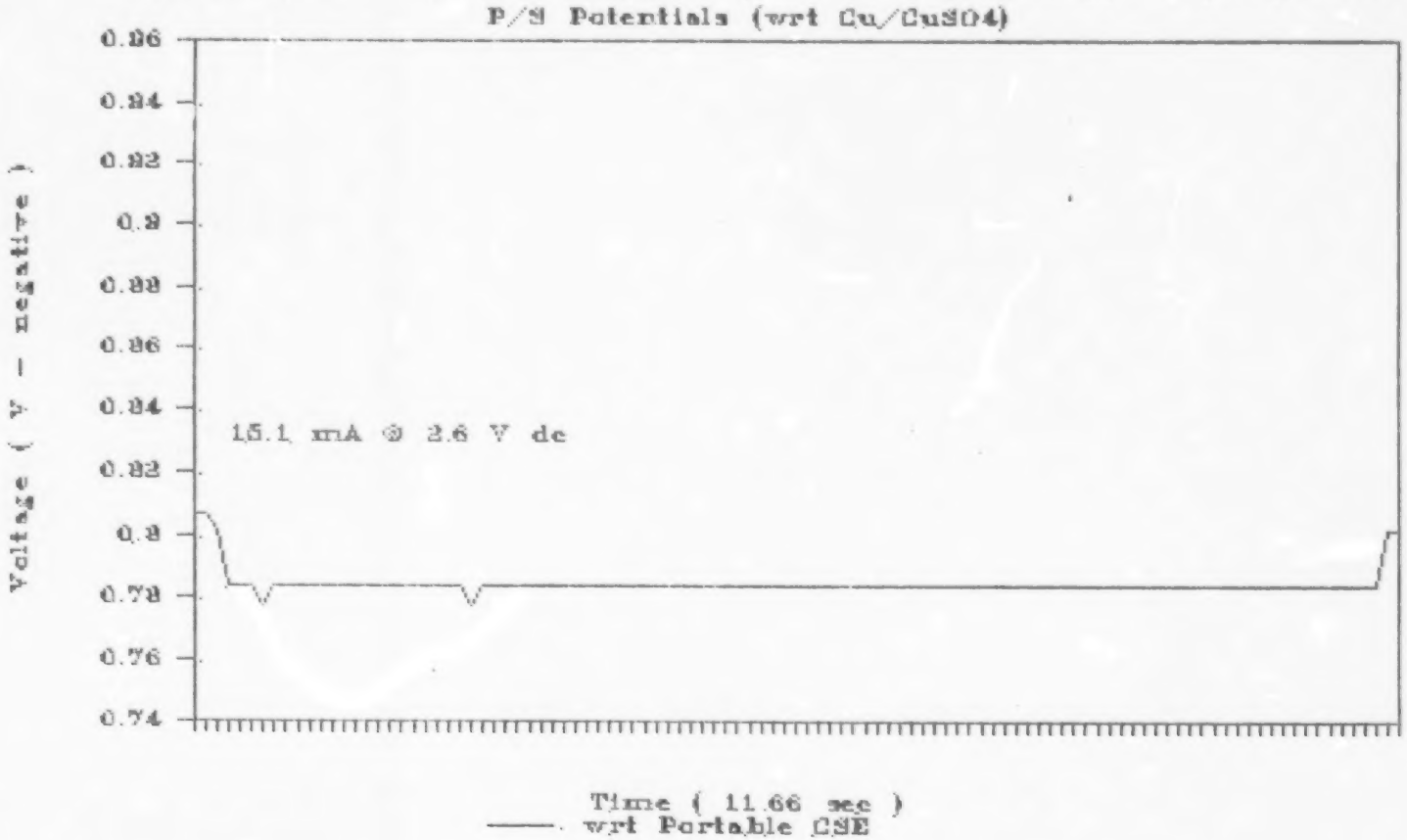

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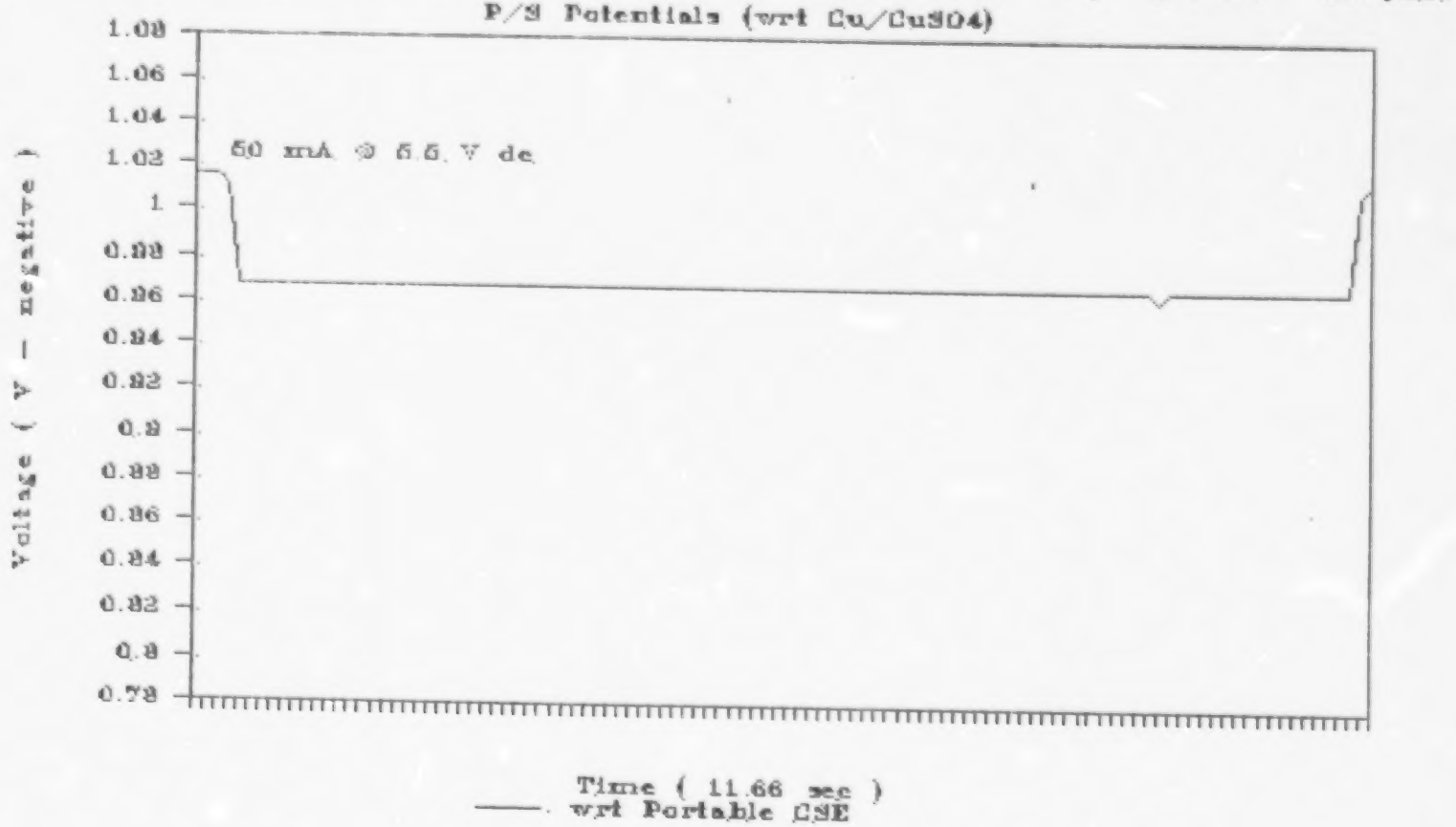

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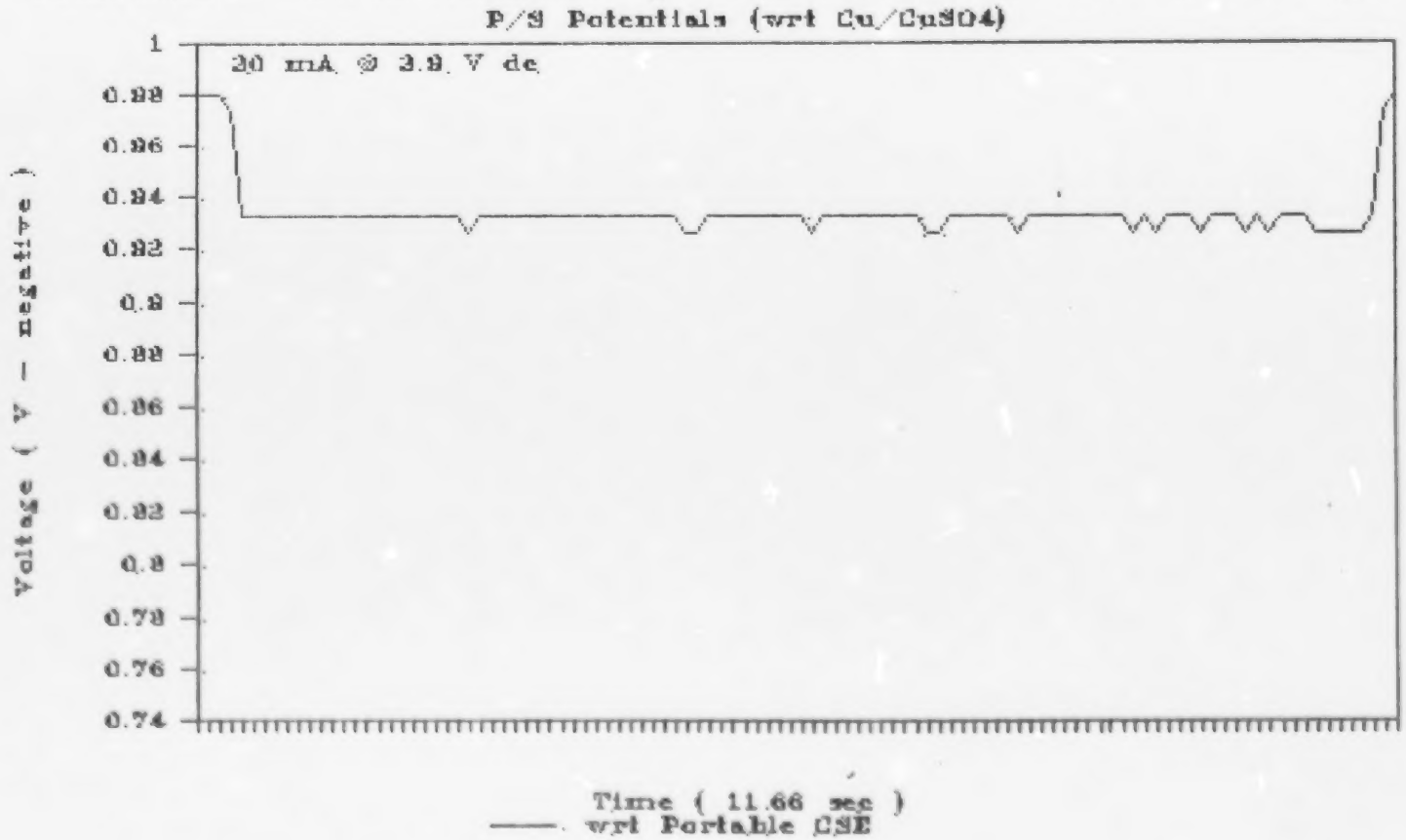

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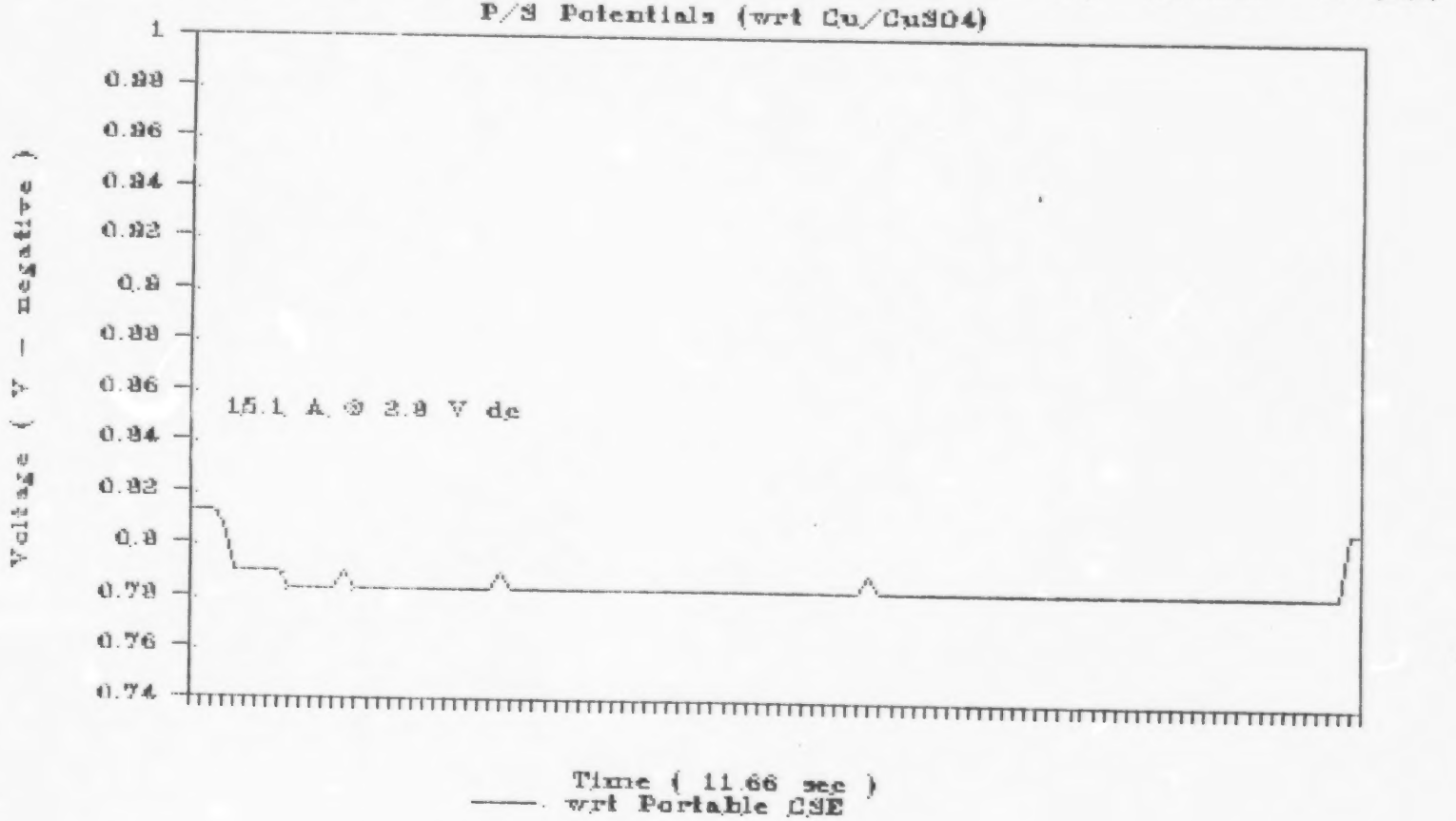

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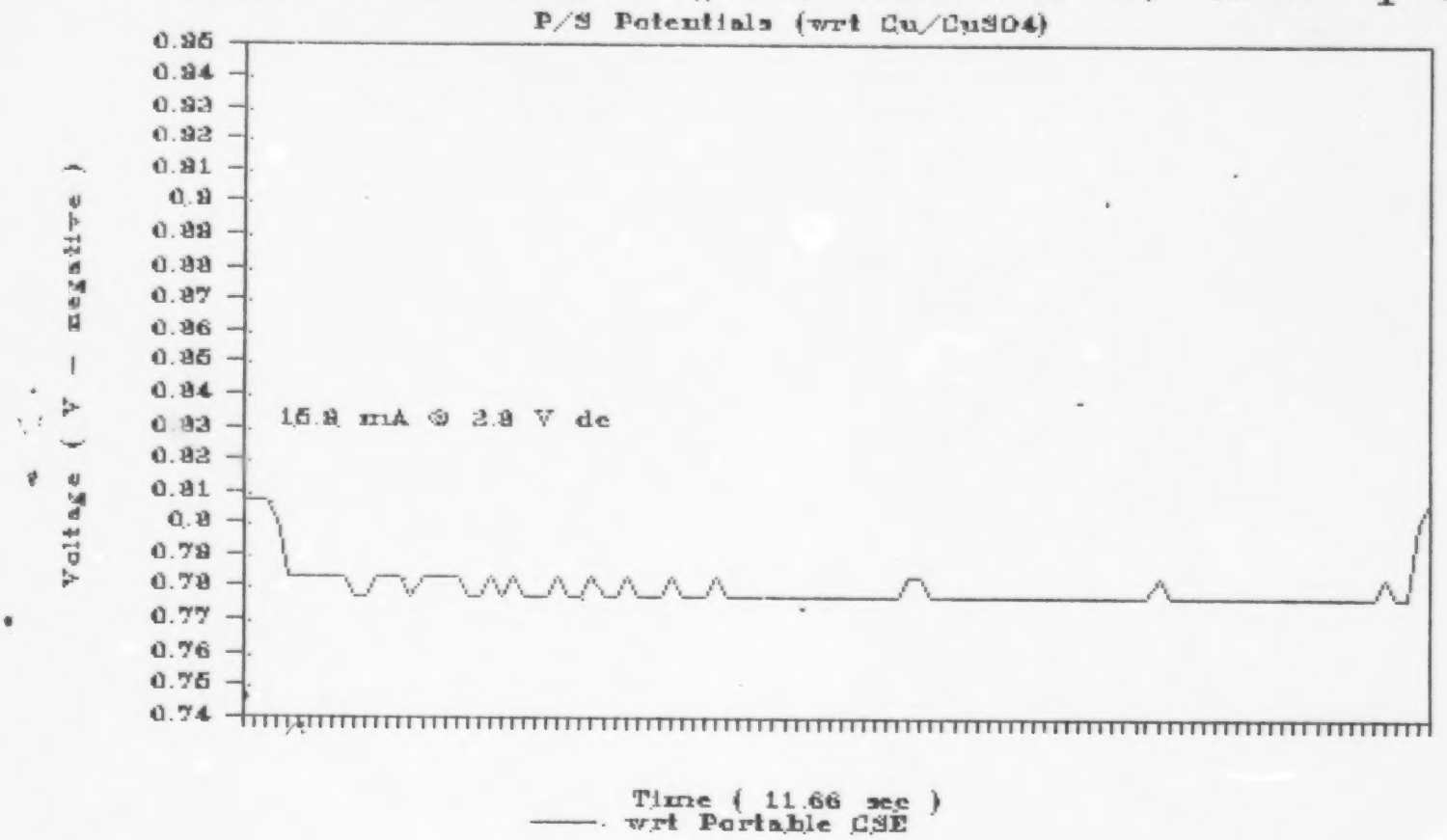

G. I. RUSSELL & COMPANY LTD.
1144 PLAINS ROAD EAST BURLINGTON ONTARIO CANADA L7S 1W6
FAX: (416) 333-4313 PHONE: (416) 634-5509

FAX LEAD SHEET

TO: Energy, Mines, and Resources,
OTTAWA, Ontario
CANMET MTL.
ATTENTION: Dr. R. W. Revie

DATE: December 21, 1989
REF: Canmet Contract 8-9180,
Serial Number 89180-01SO
FAX NO.: 1-613-992-8735

WE ARE TRANSMITTING 2 SHEETS, INCLUDING THIS LEAD SHEET.

Further to our most recent report, dated December 15, 1989, please find attached, our Proposed Procedure to Chemically Treat the Backfill.

If you have any questions, please do not hesitate to contact us.

G. I. Russell, P. Eng.,
Principal

GIR:kw

Encl.

CONSULTING ENGINEERS – PIPELINE SYSTEMS

L7S 1V
PHONE (416) 634-55(
TELEX 061-82(

G.I. Russell P.Eng. Principal
Designated Specialist (A.P.E.O. & N.A.C.E.)

December 21, 1989

CANMET

Proposed Procedure to Chemically Treat the Backfill

1. First, it is proposed that Specimen #3 is rebackfilled to provide a 1/2" layer that is deemed compatible with Cathodic Polarization, using a sand/bentonite/cement mix.

2. Demonstrate if Cathodic Protection is feasible by being at a lower current density and the usually specified minimum criterion of -850 mV to CuCuSO4 is obtained.

3. Concentrated calcium hydroxide with calcium nitrite, shall then be added, progressively to Specimen #1; to Specimen #3 calcium silicate shall be used with the concentrated calcium hydroxide.

4. Should optimum results be obtained with Specimen No. 3, then the goal is confined to determining a practical way of duplicating results in 2 above by an injection process in the field.

5. Specimen No. 2 shall remain the control, only distilled water being added when the other specimens are treated.

All as discussed and agreed on December 20 and 12, 1989 by,

W.W. Smeltzer
Dr. W. W. Smeltzer

G. I. Russell, P. Eng.

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APPENDIX "H"

Typical Potential and Current Data

a.c./d.c. to d.c.

Date	Run No.	Duration	Current			Structure 1 to Reference V	Structure #2 to Reference V
			a.c. mA	d.c. mA			
				Str. 1	Str. 2		
23/2/90	1	0 hr 0 m	37.8	1.61	1.85	-1.028	-1.048
24/2/90	1	22 hr 20 m	0	N/A	N/A	-1.075	-1.073
--	1	--	Change mV			+47 mV	+25 mV
			Increase %			4.5 %	2.4 %
22/2/90	3	0 hr 0 m	28.5	1.44	1.65	-1.087	-1.052
1/3/90	3	44 hr 10 m	0	1.46	1.69	-1.125	-1.060
--	3	--	Change mV			+38 mV	+8 mV
			Increase %			3.5 %	0.8 %

APPENDIX "H"

Typical Potential and Current Data

d.c. to a.c./d.c.

Date	Run No.	Duration	Current			Structure 1 to Reference V	Structure #2 to Reference V
			a.c. mA	d.c. mA			
				Str. 1	Str. 2		
4/3/90	8	23 hr 42 m	0.0	1.35	1.56	-1.160	-1.048
5/3/90	8	23 hr 42 m	26.4	1.42	1.60	-1.134	-1.040
--	8	--		Change mV		-26 mV	-8 mV
				Decrease %		2.3 %	0.77 %
6/3/90	10	46 hr 50 m	0.0	1.36	1.49	-1.133	-1.001
8/3/90	10	46 hr 50 m				-1.095	-0.984
--	10	--		Change mV		-38 mV	-17 mV
				Decrease %		3.5 %	1.7 %

APPENDIX "I"

Description	EVENTS			
	d.c./a.c. to d.c.		d.c. to a.c./d.c.	
	Structure #1	Structure #2	Structure #1	Structure #2
Events	8	8	7	7
Polarized	7	6	2	1
De-polarized	--	2	5	6
No Change	1	0	--	--

APPENDIX "J"

Probability Distribution of Events

EVENT: a.c./d.c. to d.c.

Polarization	De-Polarization	No Change
13	2	1

$$\text{Probability of Polarization} = \frac{13}{13 + 2 + 1} = \frac{13}{16} = 81\%$$

That is: 13 chances in 16, structure will polarize.

EVENT: d.c. to a.c./d.c.

Polarization	De-Polarization	No Change
3	11	--

$$\text{Probability of De-Polarization} = \frac{11}{3 + 11} = \frac{11}{14} = 79\%$$

That is: 11 chances in 14, Structure will De-Polarize.

APPENDIX "K"

Individual Test Events of Interest

Event	Date Time	Str. #1 to	Str. #2 to	d.c., mA Str.1	d.c., mA Str.2	a.c. supply V.ac./I a.c.	Test Duration	Comment
			a.c./d.c. to Nil					
(a)	March 17/90							
	1000 hrs.	-1.331	-1.194	2.70	2.54	--	25 hr, 25 min.	Depolarized (to native
	March 18/90	-0.451	-0.481	0	0	--		Potential)
			Nil to a.c.					
(b)	March 18/90							
	1125 +	-0.451	-0.481	0	0	8.5 mV	7 hrs, 30 min.	Polarized,
	1855	-0.623	-0.625	0	0	10.5 mA		(No comment)
			a.c. to a.c./d.c.					
(c)	March 19/90							
	0803	-0.949	-0.947	1.01	0.906	10.0 V	13 hrs.	Polarized,
						9.89 mV	8 min.	(satisfactory for small current involved)

SUMMARY OF DATA — a c STRAY CURRENT TEST

EVENT	TEST DUR	DATE TIME	$STR_1 CuCuSO_4$	$STR_2 CuCuSO_4$	dc ma STR_1	dc ma STR_2	ac SUPPLY	POLARIZATION CHANGE FROM dc ac TO dc STR_1	POLARIZATION CHANGE FROM dc ac TO dc STR_2	POLARIZATION CHANGE FROM dc TO dc ac STR_1	POLARIZATION CHANGE FROM dc TO dc ac STR_2
		FEB 23	-1.315	ac ON dc ON	1.61	1.85	15.4 V 37.8 ma				
1	22hr 20m	13:15 14:45	-1.028	-1.048							
			ac OFF/ dc ON								
		FEB 24 11:35	-1.075	-1.073				+4.5%	+2.4%	—	—
2	99hr 10m	11:38	ac ON / dc ON								
		FEB 26 08:10 14:45	-1.087	-1.052	1.34 1.44	1.55 1.65	15.45 V 28.4 ma 26.8 ma	—	—	+1.1%	-2.0%
		15:27 15:45	ac OFF/dc ON								
3	44hr 10m		-1.100	-1.056	1.46	1.65		+3.5%	+0.76%	—	—
		MAR 1 09:20	-1.080	-1.042	1.32	1.54					
		MAR 2 10:55	-1.125	-1.060	1.46	1.65					
4	40m	11:05 11:06	ac ON/dc ON -1.136	-	1.411	-	28.5 ma	—	—	-0.26%	-0.57%
		11:45	-1.122	-1.054	1.44	1.72					
5	12m	15:50 15:53	-1.095	-1.020 Y							
		16:02	ac OFF/dc ON -1.105	-1.033 Y	-	-		+0.9%	+1.3%	-	-
6	19hr 23m	16:03 16:10	ac ON/dc ON -1.105	-1.032 Y							
		MAR 3 11:33	-1.131	-1.057 Y	1.46	1.68	29.3 ma	—	—	+2.3%	+2.3%
7	23hr 57m	11:45 12:25	ac OFF/dc ON -1.150	-1.064 Y	1.47	1.70		+2.5%	-0.86%	—	—
		MAR 4 11:30	-1.160 Y	-1.048 Y	1.35	1.56					
8	23hr 42m	11:37 11:52	ac ON/dc ON -1.131 Y	-1.051 Y	1.42	1.60	26.4 ma	—	—	+2.3%	-0.77%
		MAR 5 10:55 11:12	-1.134 Y	-1.040 Y	1.42	1.55	15.5 V 25.7 ma				
9	24hr 33m	12:00	ac OFF/dc ON								
		MAR 6 11:45	-1.133	-1.001	1.36	1.49		+1.2%	-2.8%	—	—
10	46hr 50m	11:58	ac ON/dc ON		(ac SUPPLY CHANGED)						
		12:03	-1.132	-0.995	1.36	1.49	10.3 V 15.5 ma				
		MAR 7 08:23	-1.091	-1.001	1.38	1.49	15.0 V	—	—	-3.5	-1.7
		MAR 8 10:35	-1.095	-0.984	1.36	1.46	14.6 ma (VIA'S") 10.35V 14.7ma				
11	48hr 35m	10:47 11:33	ac OFF/dc ON -1.093	-0.999	1.35	1.45					
		MAR 9 12:15	-1.099	-0.978	1.34	1.43					
		MAR 10 11:05	-1.095	-0.970	1.35	1.40		-0.09%	+6.7%	—	—
		11:35	-1.103	-1.049	1.41	1.42					
		13:10	-1.094	-1.050	1.40	1.42					
12	22hr 50m	13:20 13:22	ac ON/dc ON -1.097	-1.036			10.35 V 12.6 ma	—	—	-4.3%	-4.6%
		MAR 11 11:00	-1.048	-1.004	1.35	1.41					

IMPRESSED CURRENT METHOD WITH COMPUTERIZED DATA ACQUISITION SYSTEM

EVENT	TEST DUR.	DATE TIME	$STR_1 CuCuSO_4$	$STR_2 CuCuSO_4$	dc ma STR_1	dc ma STR_2	ac SUPPLY	dc SUPPLY	FROM dc ac TO dc STR_1	FROM dc ac TO dc STR_2	FROM dc TO dc ac STR_1	FROM dc TO dc ac STR_2	
		MAR 19 08:03	ac ON / dc ON -0.949	-0.947	1.01	0.906	8.47 V	150 mv					
		09:25 14:35	ac OFF / dc ON -0.947	-0.918	0.914	0.676	9.89 ma 0	150 mv	NOTE: 1.0 ma dc NOT SUFFICIENT TO HOLD dc POLARIZATION				
		MAR 20 08:10	-0.848	-0.943	1.06	0.901	0	150 mv					
13	8hr 15m	09:20 09:24			1.06	0.901	0	150 mv					
		09:30 16:25	-1.210 -1.236	-1.167 -1.215	1.96 1.79	1.59 1.52	0 0	535 mv 535 mv	+45.7% 69 %	+280% INCREASE I_{dc} TO STRUCTURES	-	-	SEE FIGURE 10,11
14	18hr 30m	16:35 16:35+ 16:46	ac ON / dc ON -1.234	-1.107	1.64	1.44	2.51 V 2.41ma	62.5mv 600 mv	14%	DECREASE I_{dc} TO STRUCTURES			SEE FIGURE 12,13
		MAR 21 10:45 10:55	-1.035	-1.058	1.57	1.33	2.53 V 2.35 ma	332 mv	-	-	-19.4%	-14.8%	SEE FIGURE 14,15
15	5hr 31m	11:16 11:23 15:39 15:46	ac OFF / dc ON -1.053	-1.061	158	1.34	0	410 mv	+1.7%	+0.28%	—	—	SEE FIGURE 16,17 SEE FIGURE 18,19

LEGEND

Y YELLOW $CuCuSO_4$ REF. H_g